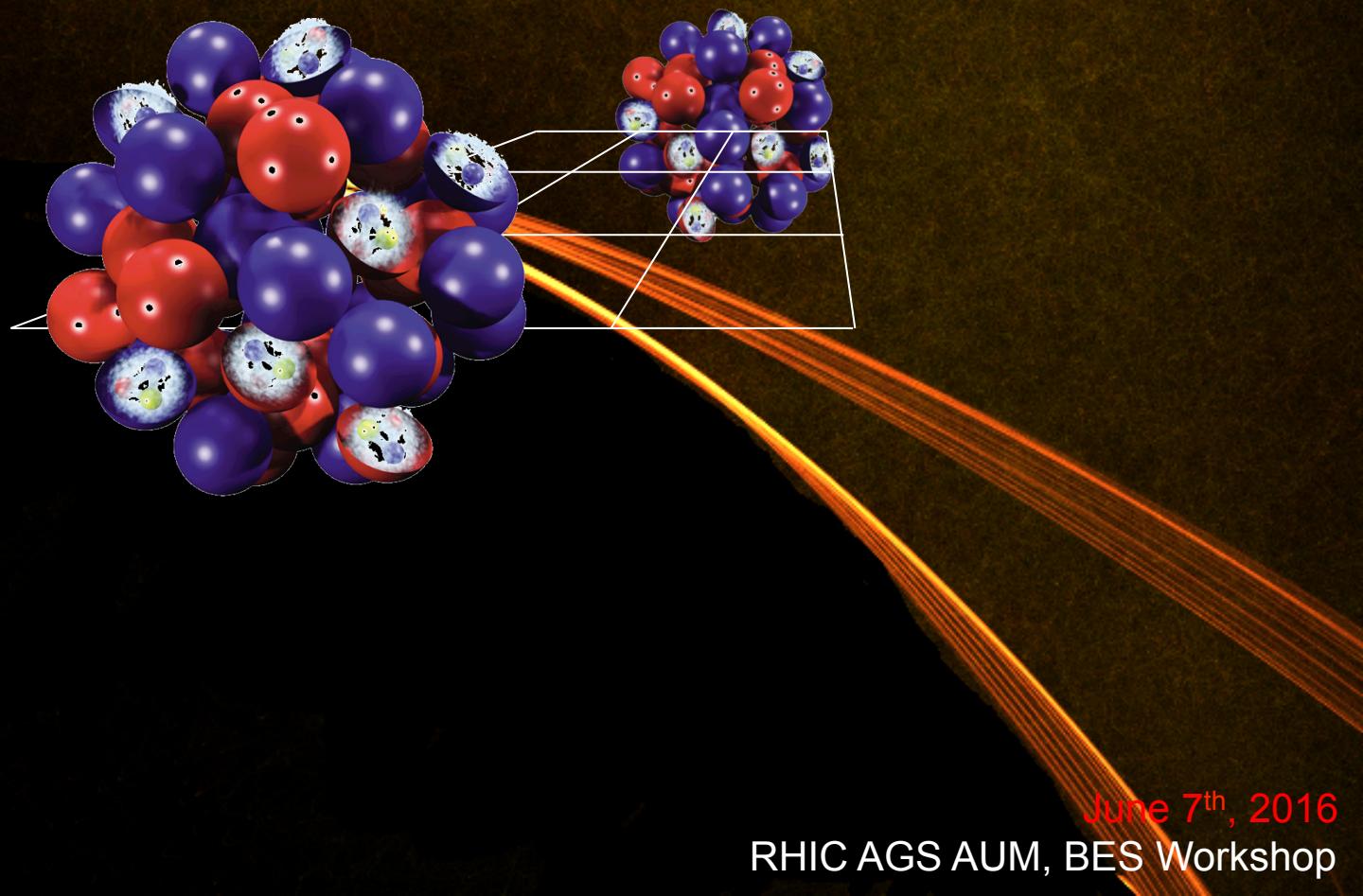


Ripples of the QGP and the QCD phase diagram



Paul Sorensen

BROOKHAVEN
NATIONAL LABORATORY

June 7th, 2016

RHIC AGS AUM, BES Workshop

What I hope you'll take away from today

Models suggest v_3 is a good indicator for the presence of a low viscosity QGP phase

Measurements show that for sufficiently central collisions, v_3 persists down to the lowest energies at RHIC

For peripheral collisions however, we find that v_3 disappears in lower energy collisions

The energy dependence of v_3 and other observables seems to suggest an anomalously low pressure in the matter created in heavy ion collisions with \sqrt{s}_{NN} near 15-20 GeV

Major Advances in Early RHIC Years

First years of Au+Au

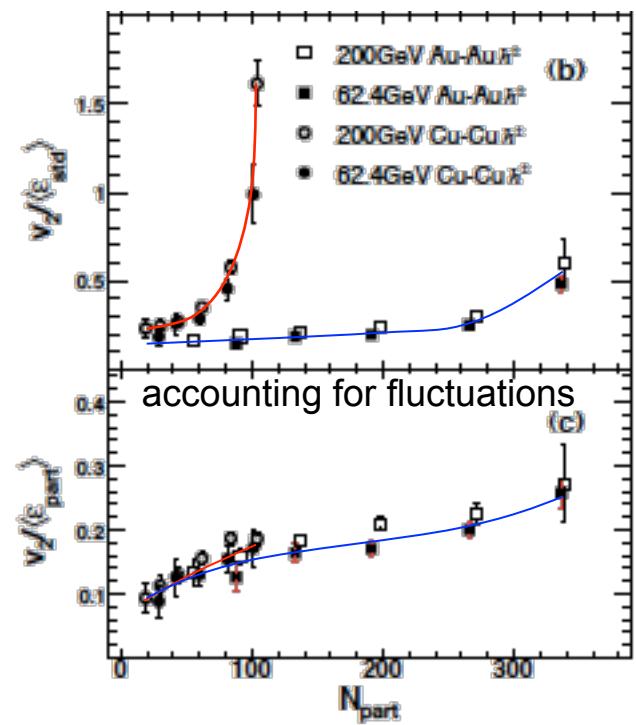
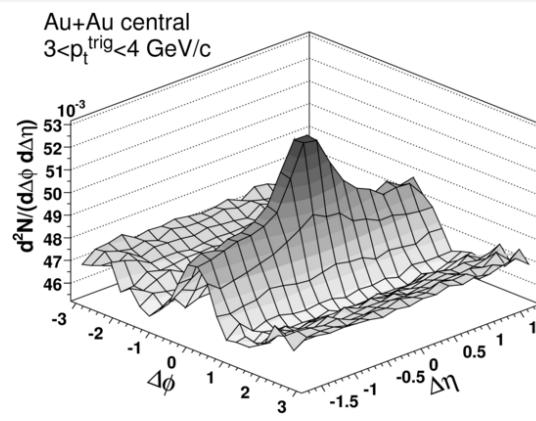
- Perfect fluidity
- Suppression of high p_T particles
- Observation of the long-range correlations (ridge)

First d+Au Run

- Opacity of the plasma phase
- Evidence of gluon saturation

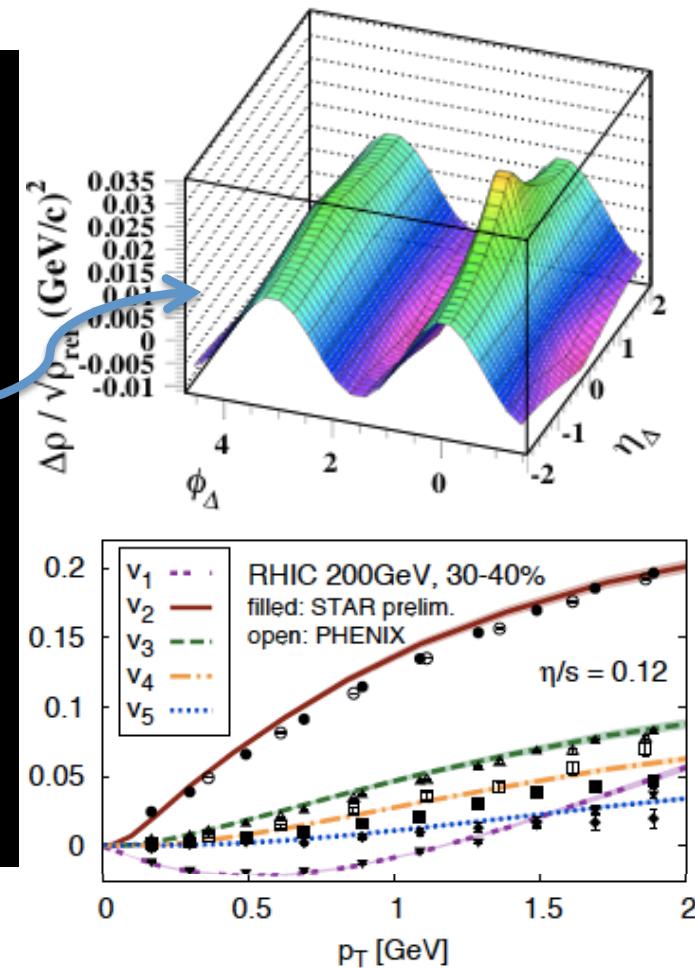
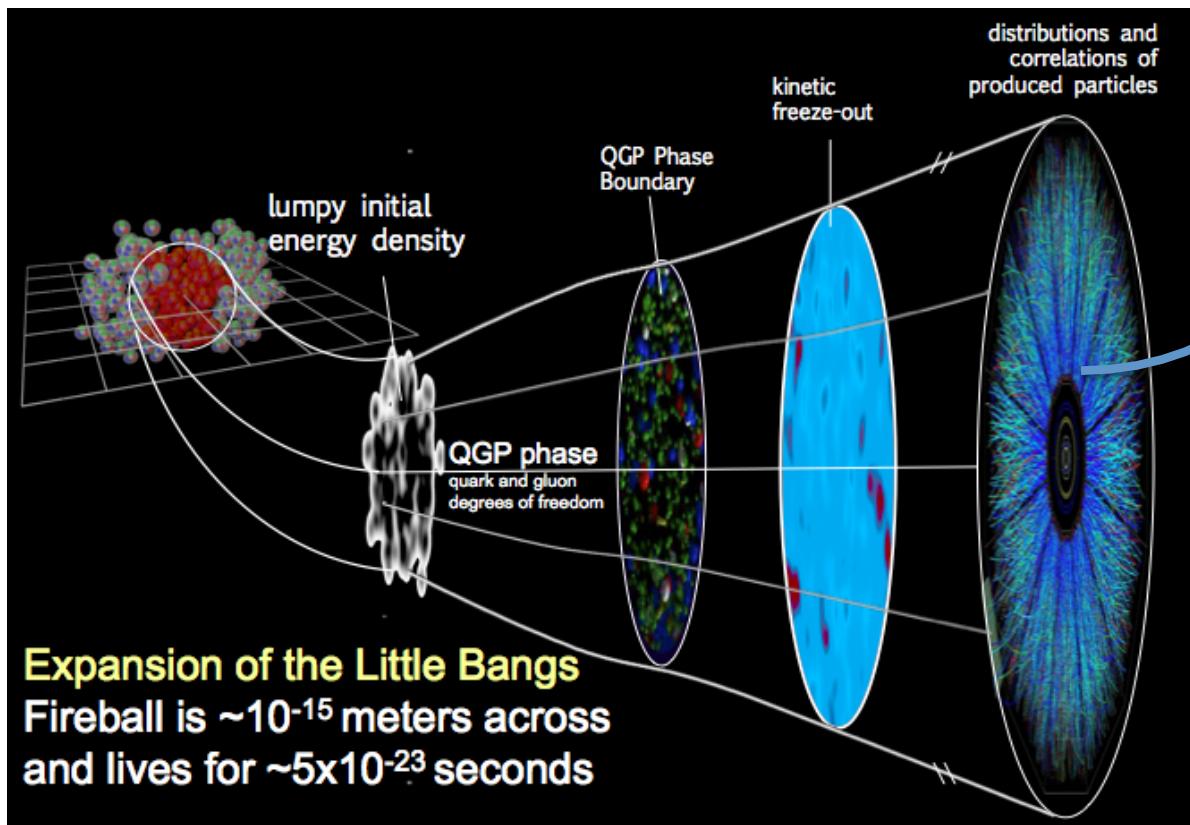
First run with Cu+Cu

- Importance of fluctuations



Smaller system revealed importance of initial state fluctuations

Standard Model of the Little Bangs

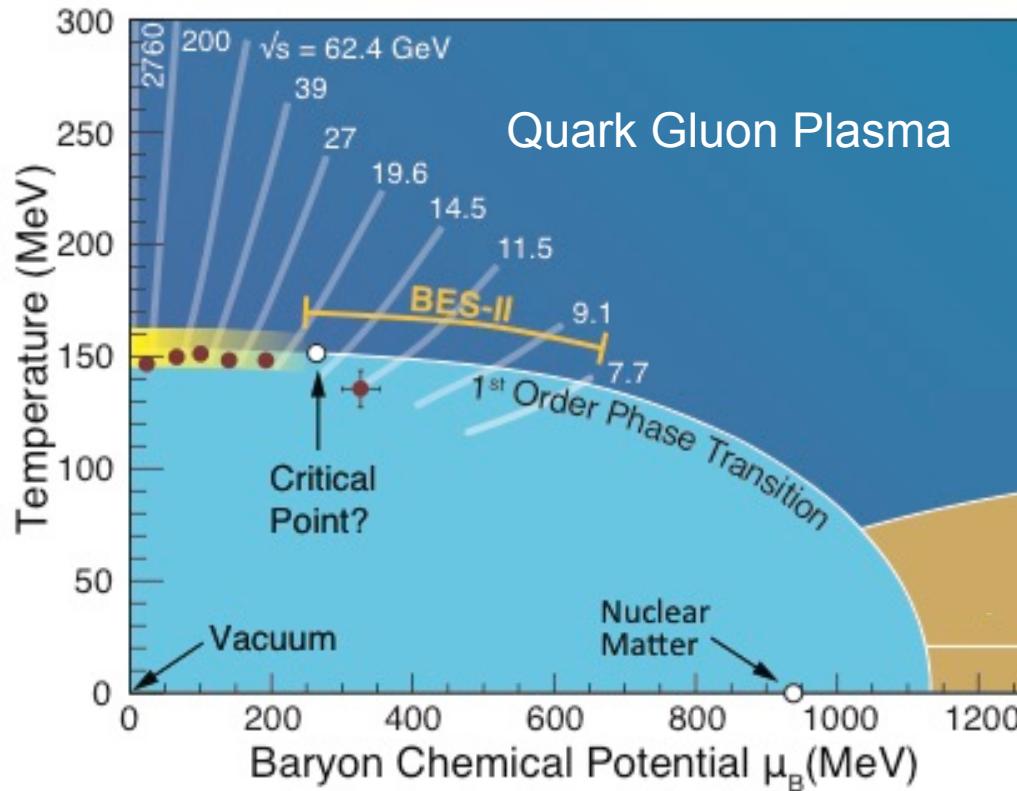


Long range correlations understood as arising from initial state density fluctuations. Conversion into momentum space requires a low η/s plasma

Sensible to express as v_n . Jettiness/non-flow subdominant until higher p_T

Studying the Phases of QCD with RHIC

a unique capability -- a unique opportunity



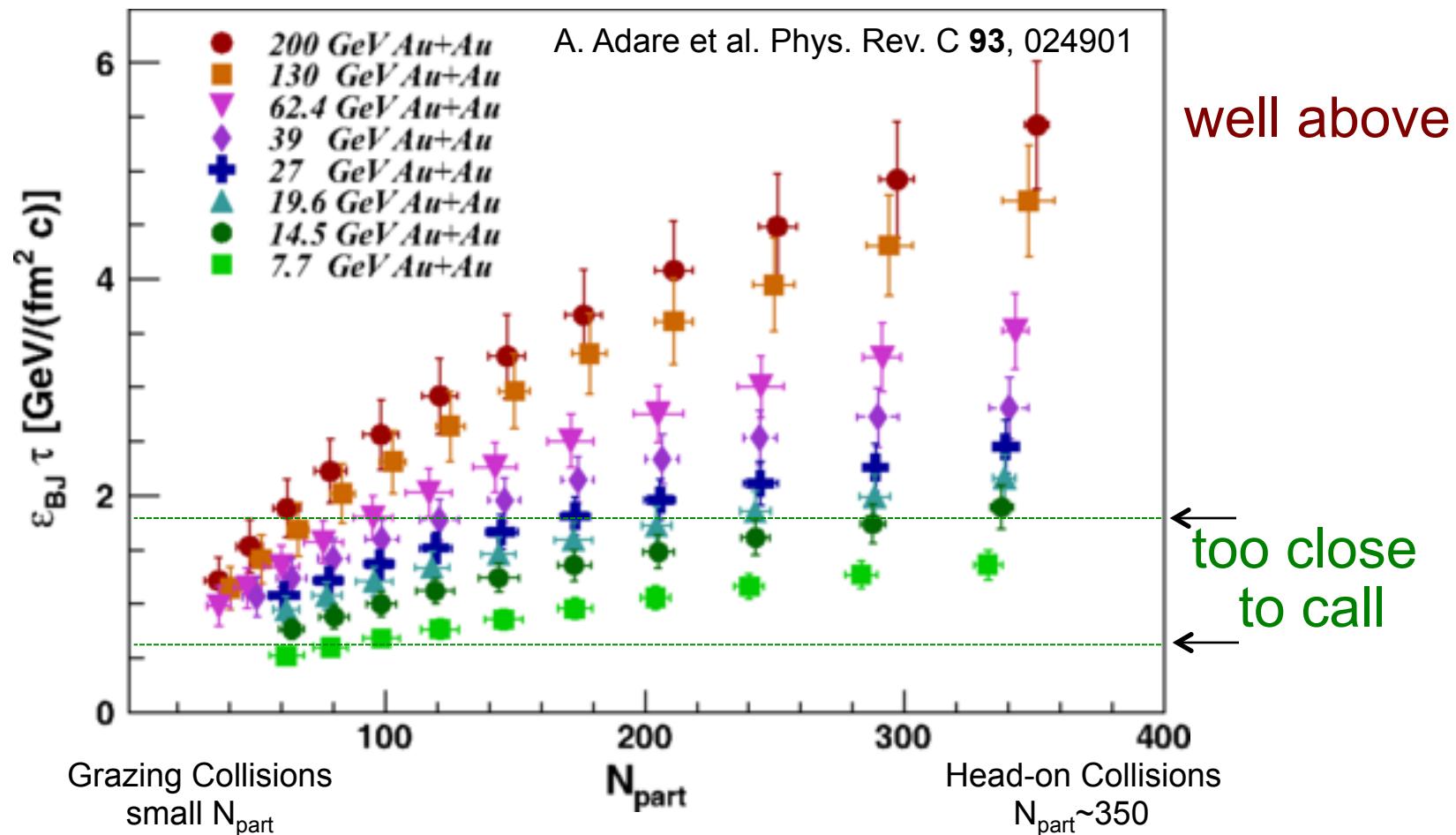
Breaking of chiral symmetry in QCD generates 99% of the visible mass of the universe. Is chiral symmetry restored in these collisions?

At low density, the phase transition between QGP and hadrons is smooth. Is there a 1st order transition and a critical point at higher density?

But first, is a QGP created in the lower energy collisions?

Do We Create QGP at Lower Energies?

Energy density measurements from exploratory scan: BES-I 2010-2014

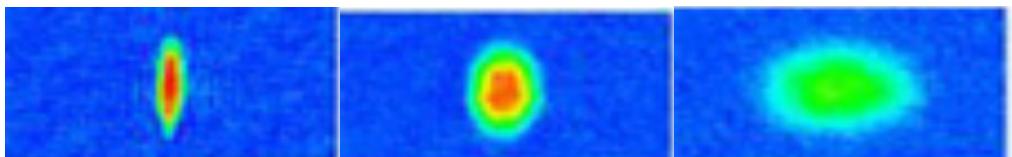


The minimum $\varepsilon_c \tau$ for QGP formation is between 0.6-1.8 GeV/fm²

BES-I exploratory scan was carried out to shed light on this question

Elliptic Flow: 7.7 GeV to 2.76 TeV

coordinate-space anisotropy into momentum-space

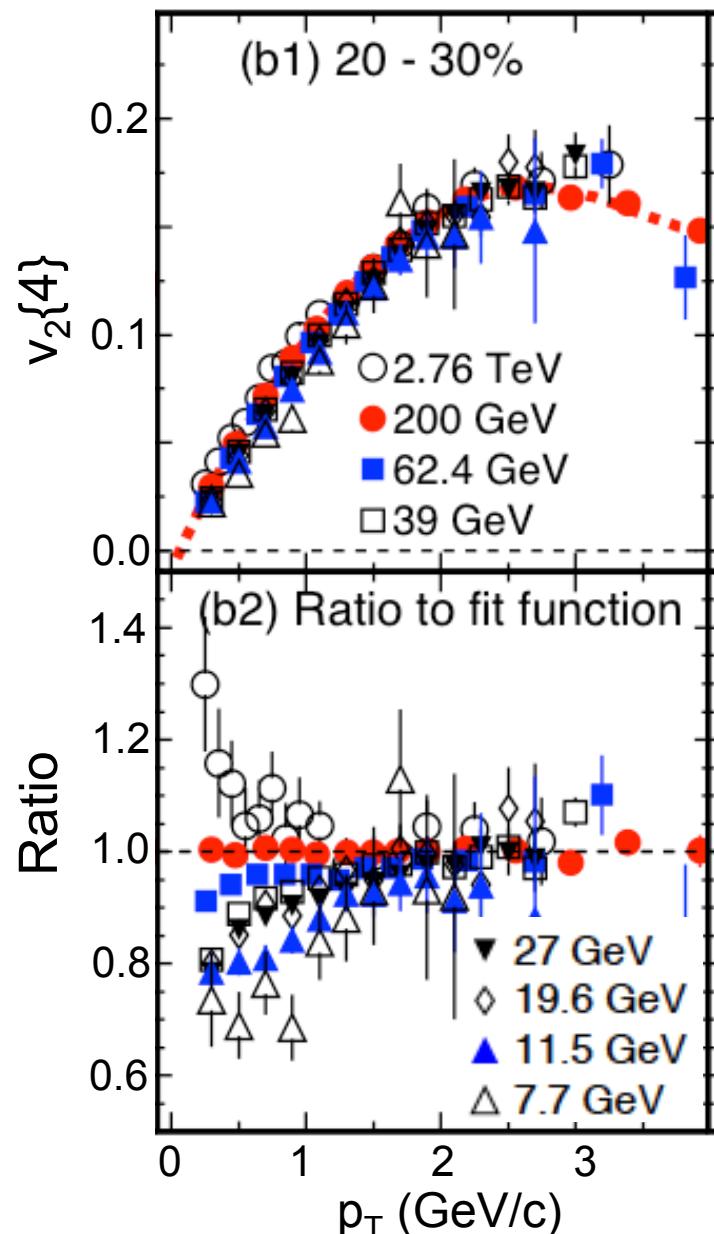


Surprisingly consistent as the energy changes by a factor ~ 400

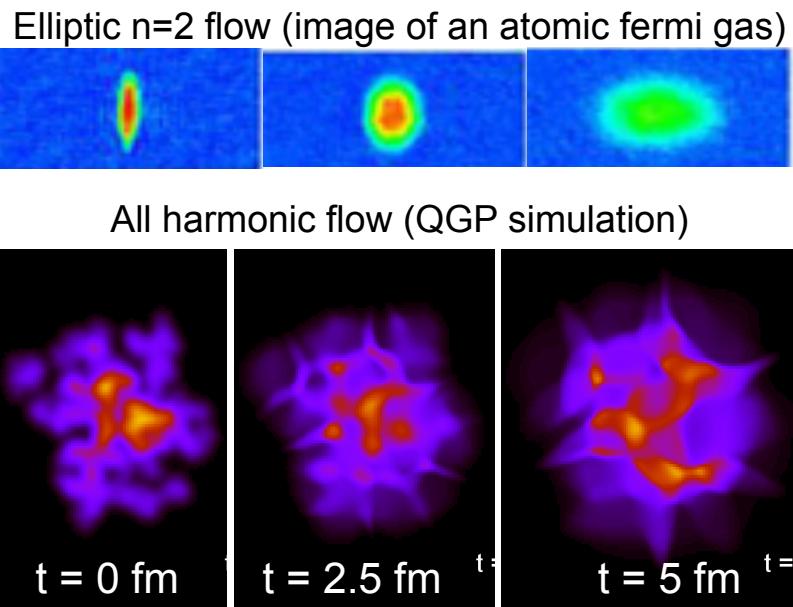
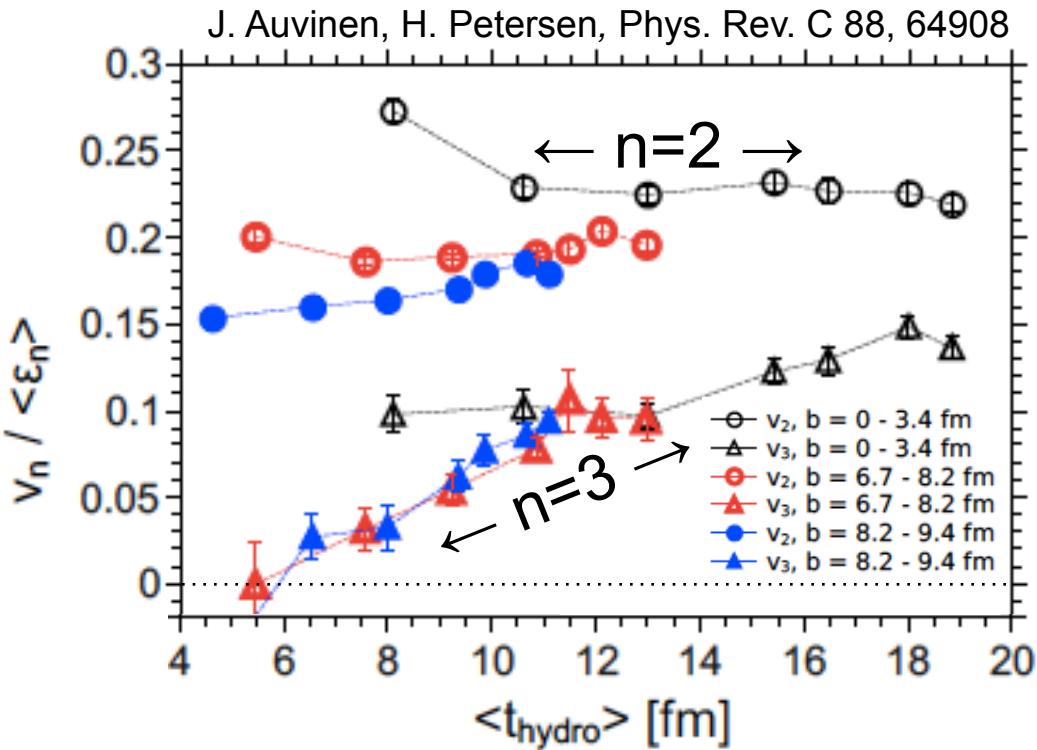
Initial energy density changes by nearly a factor of 10

No evidence from v_2 for a turn off of the QGP

How sensitive is v_2 to QGP?



Do We Create QGP at Lower Energies?



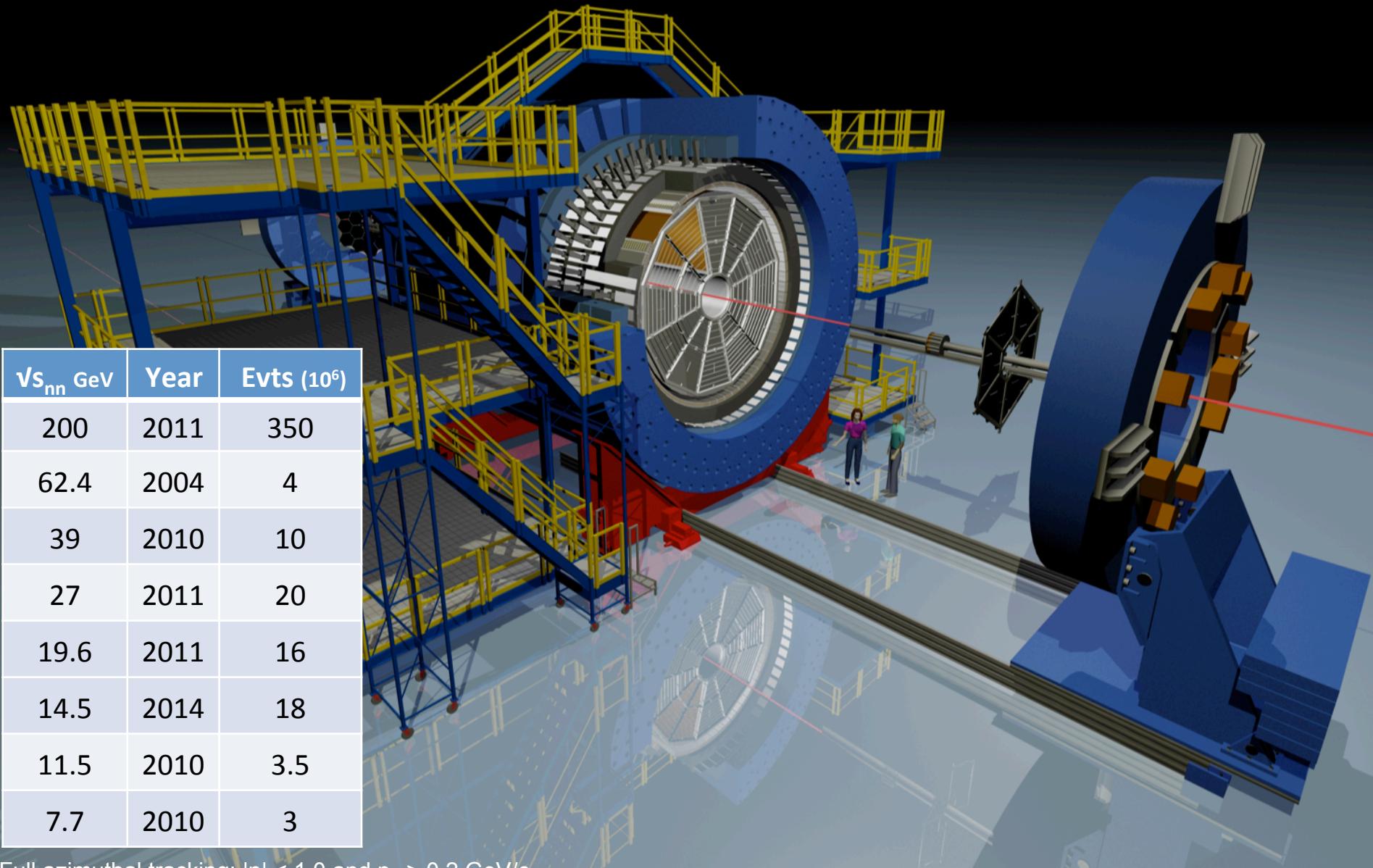
B. Schenke et.al., Phys. Rev. C 85, 024901

Models show that higher harmonic ripples are more sensitive to the existence of a QGP phase

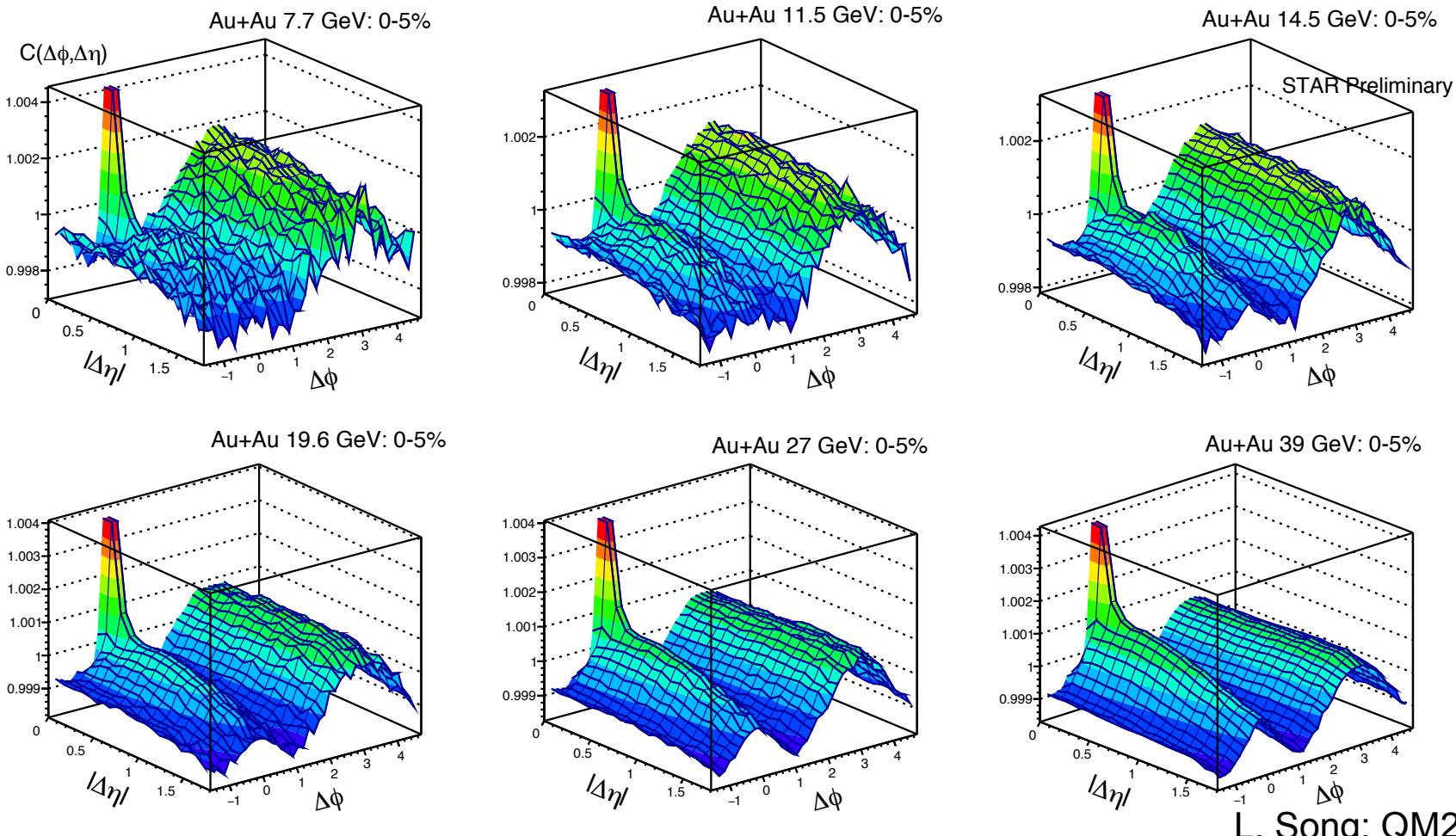
In models, v_3 goes away when the QGP phase disappears

Detector and Data Sets

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



Correlations Functions

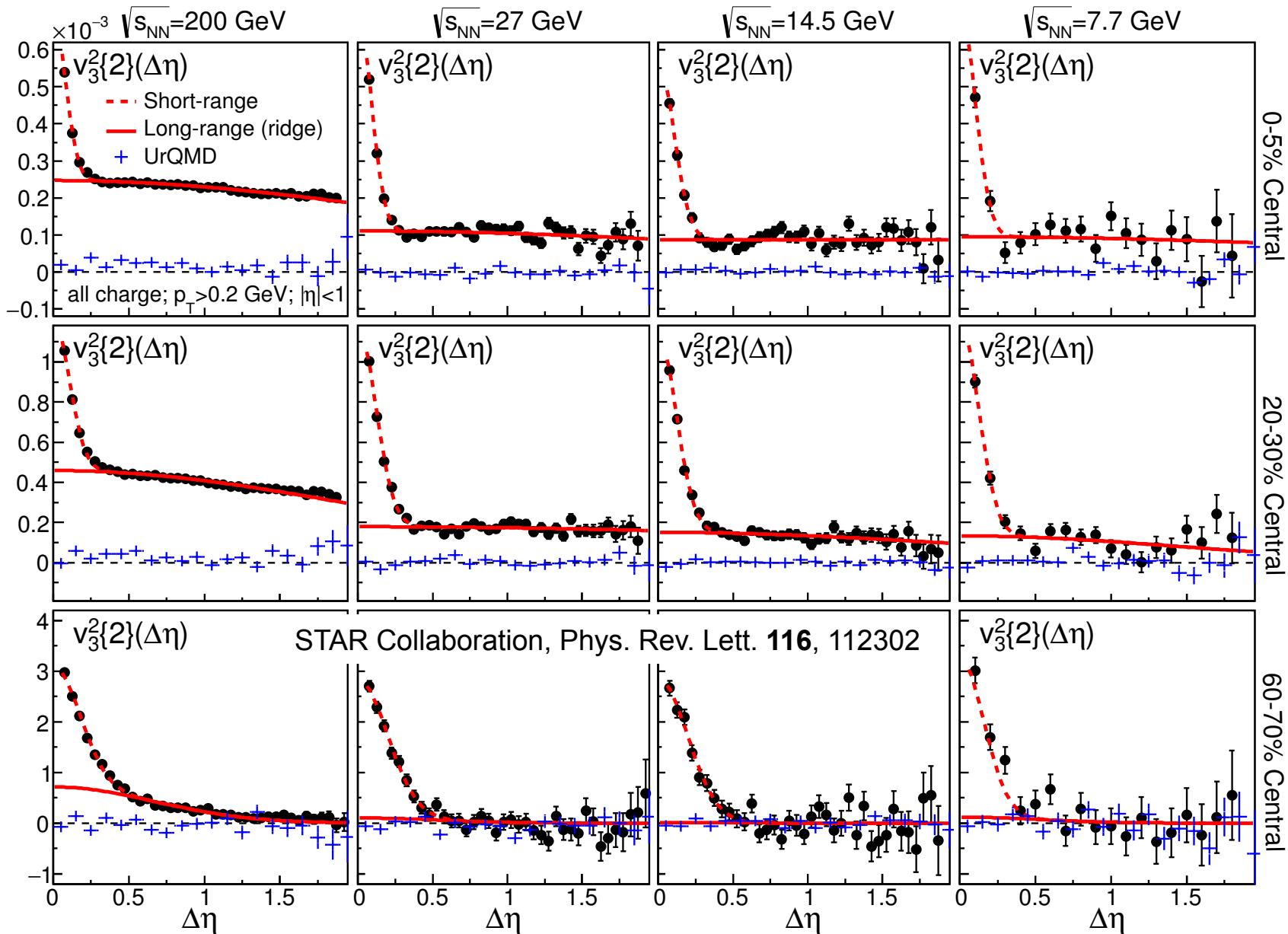


L. Song; QM2015

Correlations can be decomposed into $\Delta\eta$ dependent harmonics

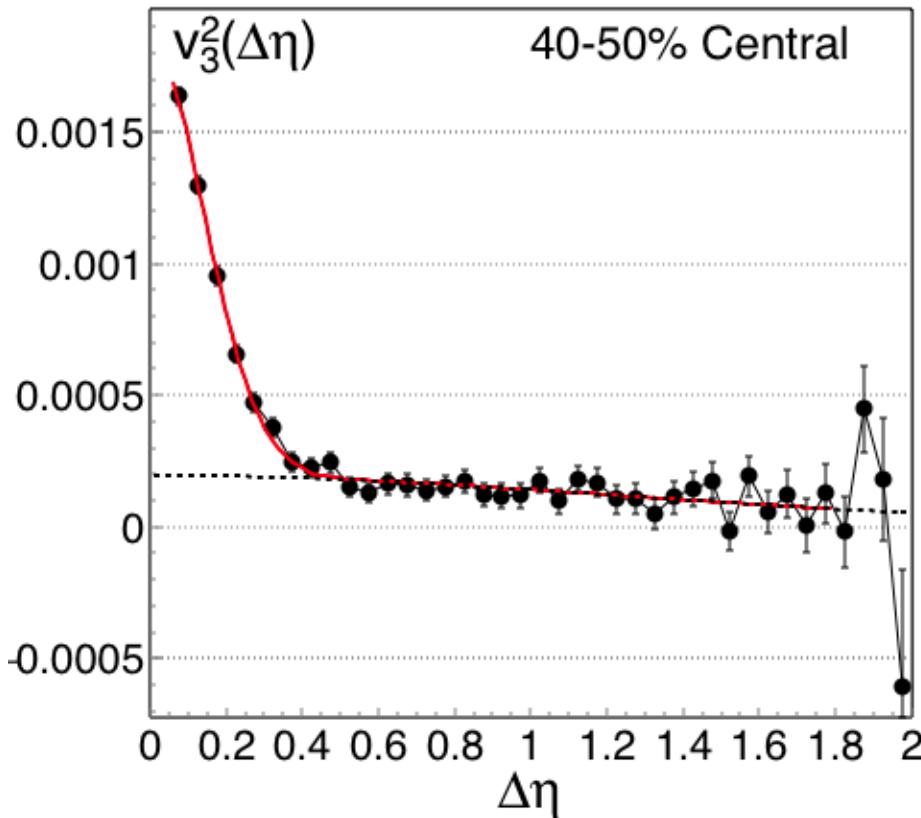
$$v_n^2 \{2\}(\Delta\eta) = \langle \cos n(\varphi_1 - \varphi_2) \rangle = \sum \frac{dN}{d\Delta\varphi} \cos(n\Delta\varphi) d\Delta\varphi \Bigg/ \sum \frac{dN}{d\Delta\varphi} d\Delta\varphi$$

3rd Harmonic Decomposition



$\Delta\eta$ Integrated Results

27 GeV



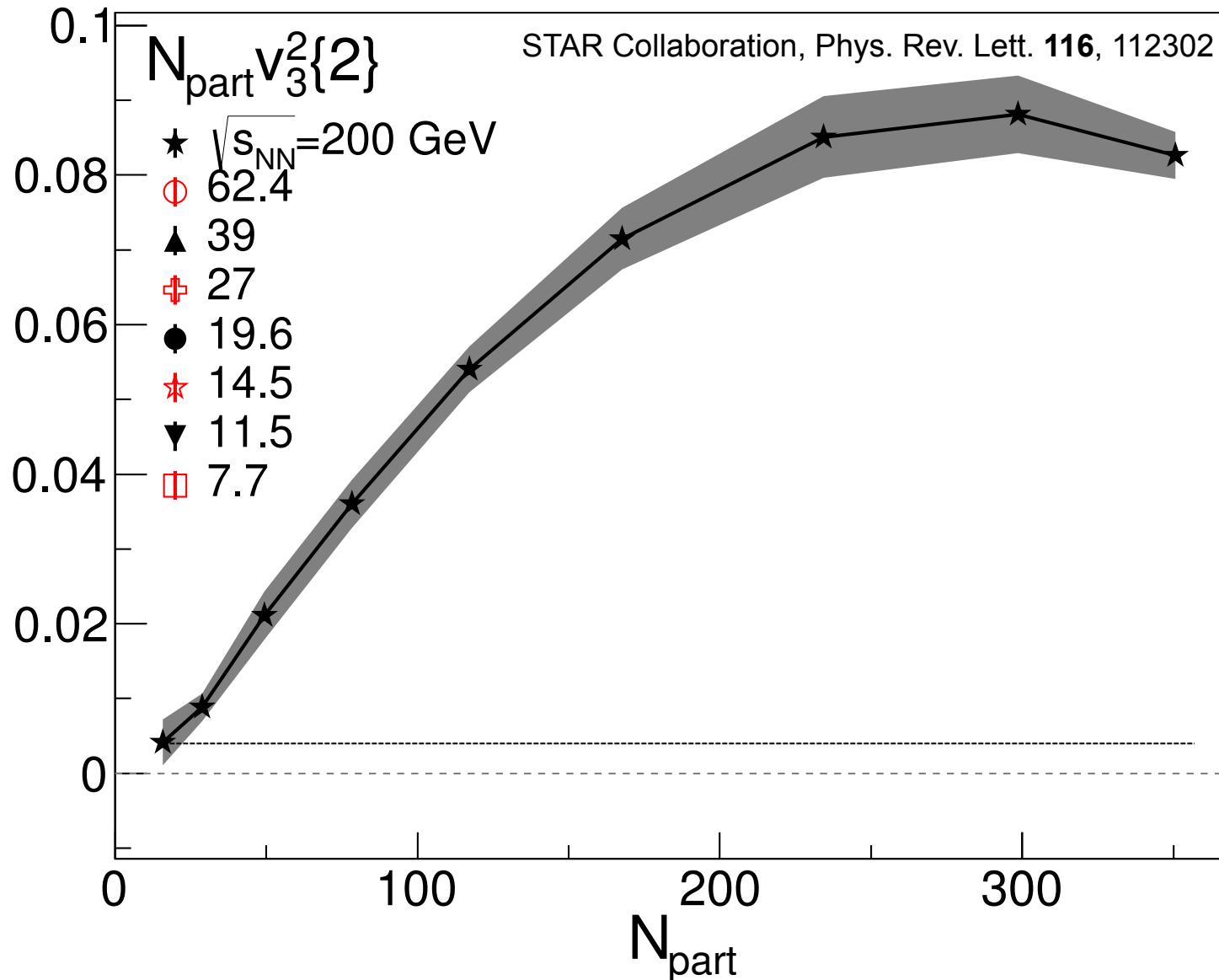
Integrate over the whole $\Delta\eta$ range but subtract off short-range contribution

$$v_n^2 \{2\} = \frac{\sum_i (v_n^2 \{2\}(\Delta\eta_i) - \delta_i) \frac{dN_i}{d\Delta\varphi_i}}{\sum_i \frac{dN_i}{d\Delta\varphi_i}}$$

Acceptance and efficiency corrected results for $p_T > 0.2$ GeV and $\eta < 1$ with no arbitrary $|\Delta\eta|$ cuts: easy for model comparisons and study of energy trends

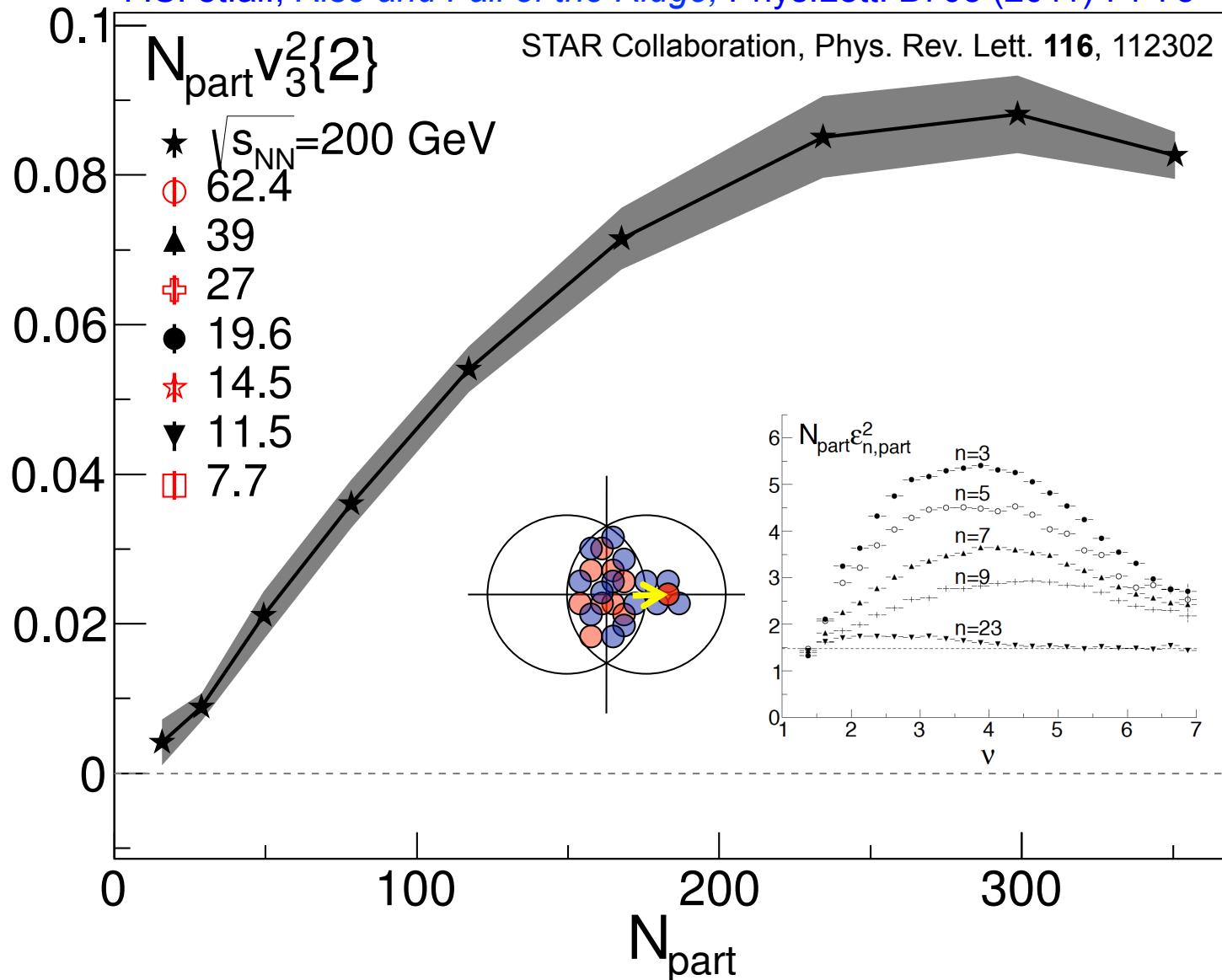
Centrality Dependence

N_{part} scales out trivial $1/N$ system size dependence: *linear superposition of $N+N$*



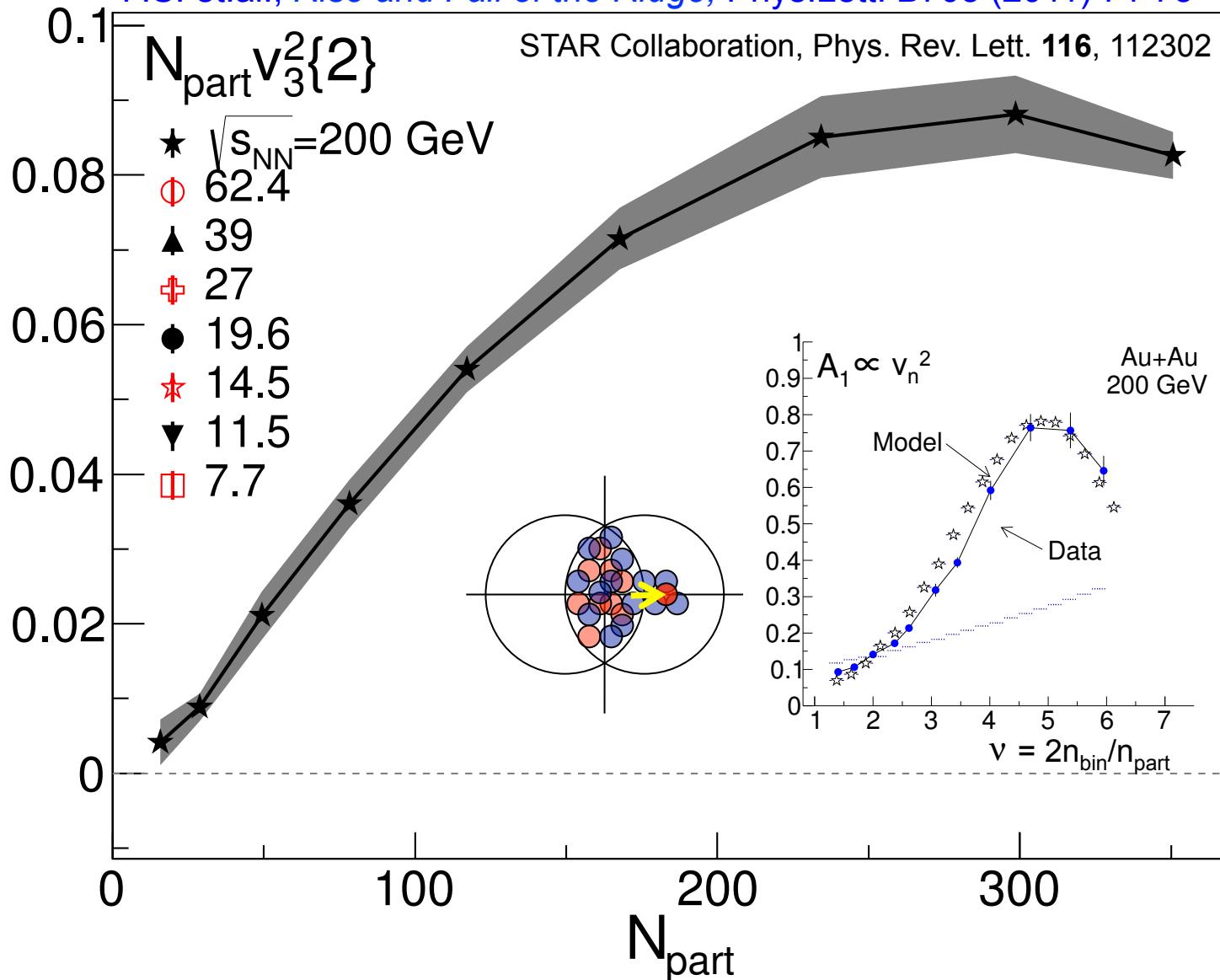
Centrality Dependence

Centrality dependence well understood in terms of initial geometry:
P.S. et.al., *Rise and Fall of the Ridge*, Phys.Lett. B705 (2011) 71-75



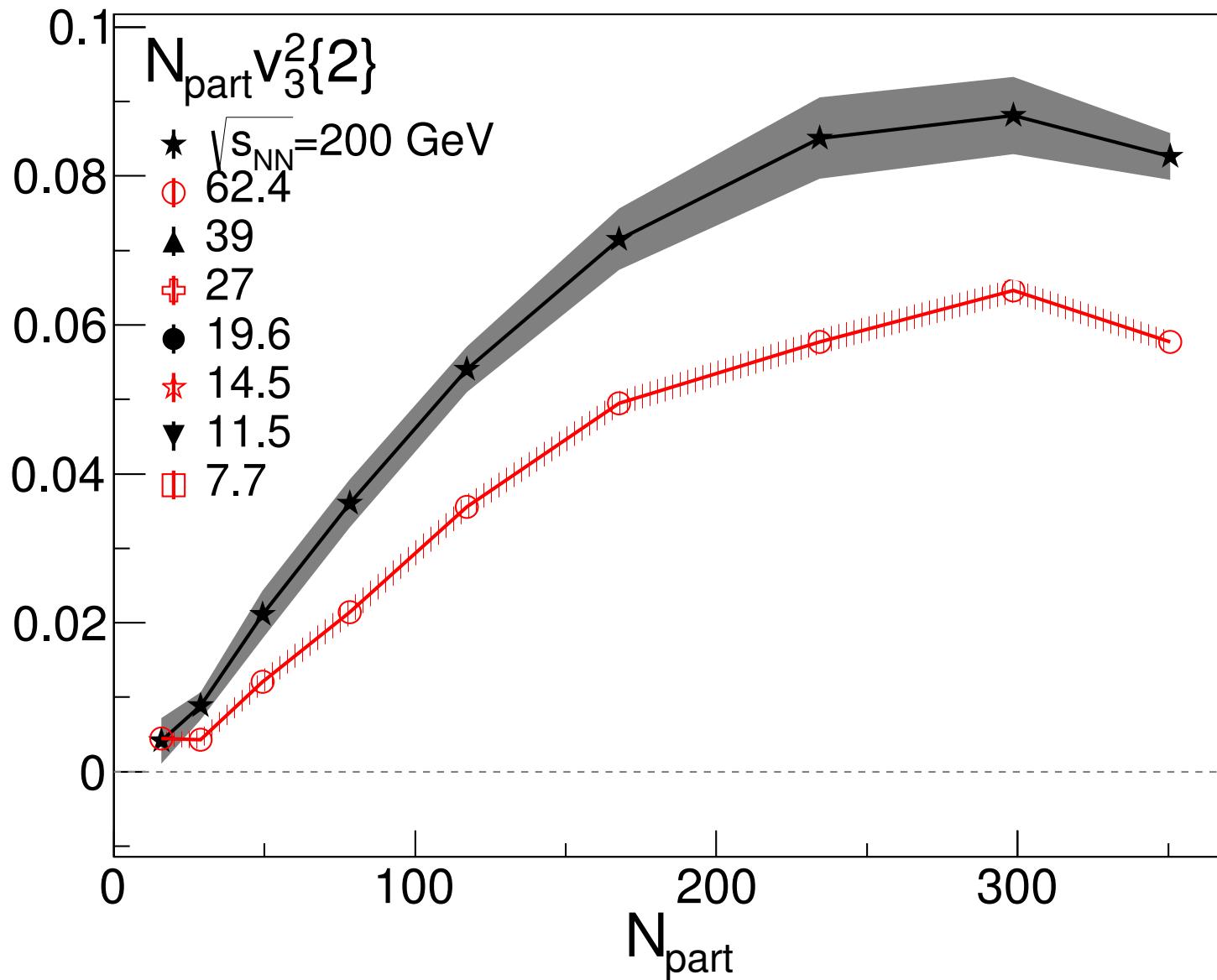
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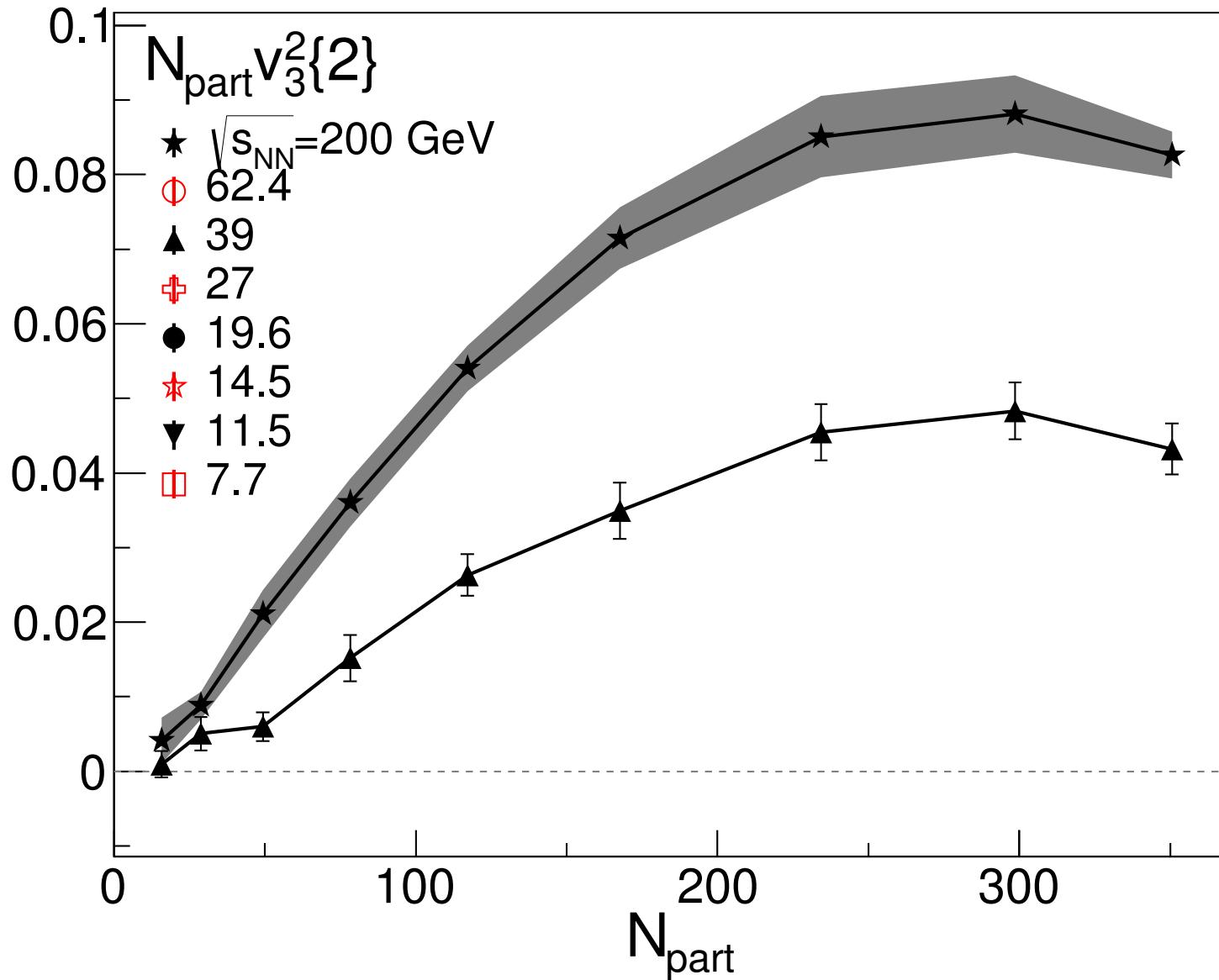
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



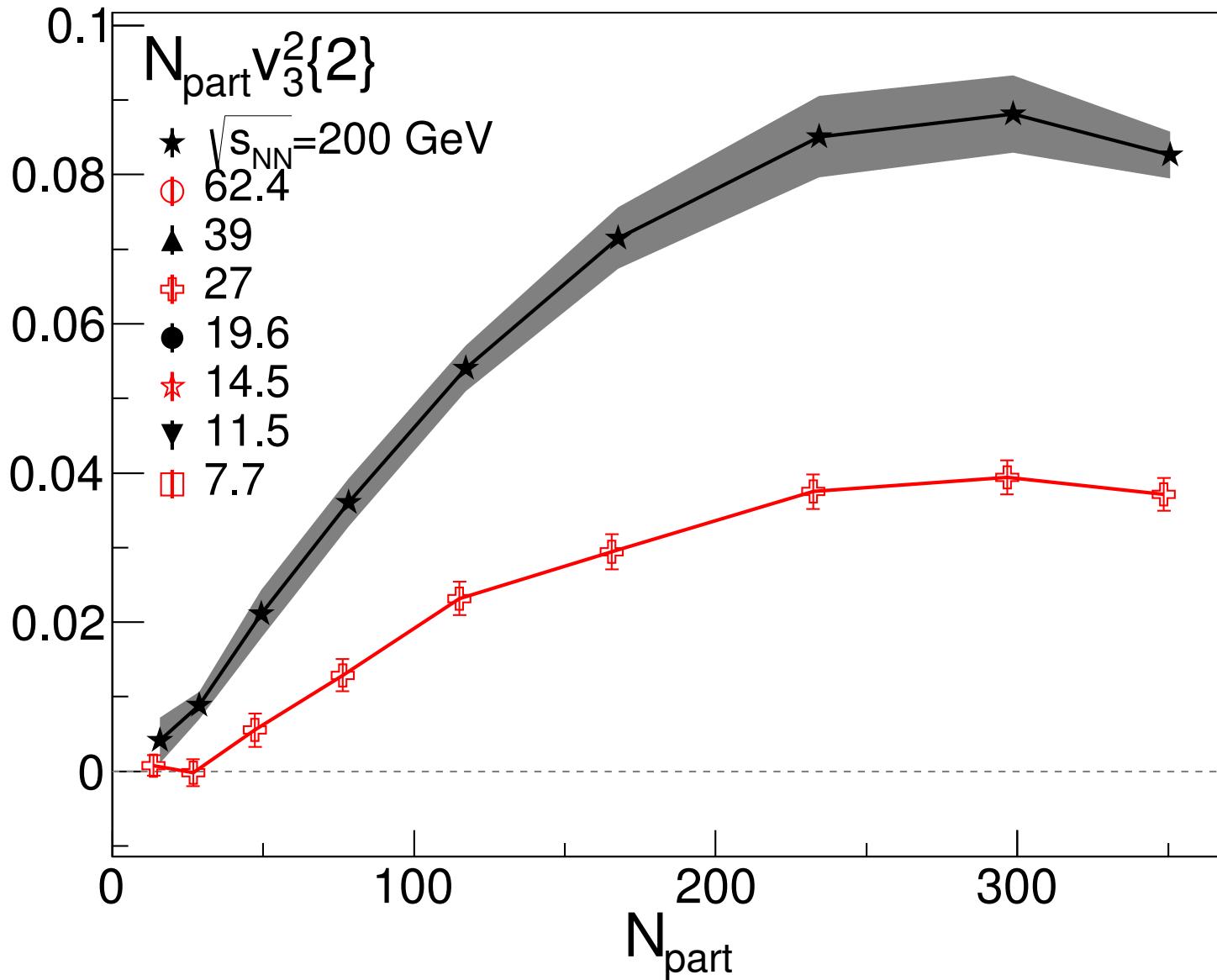
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



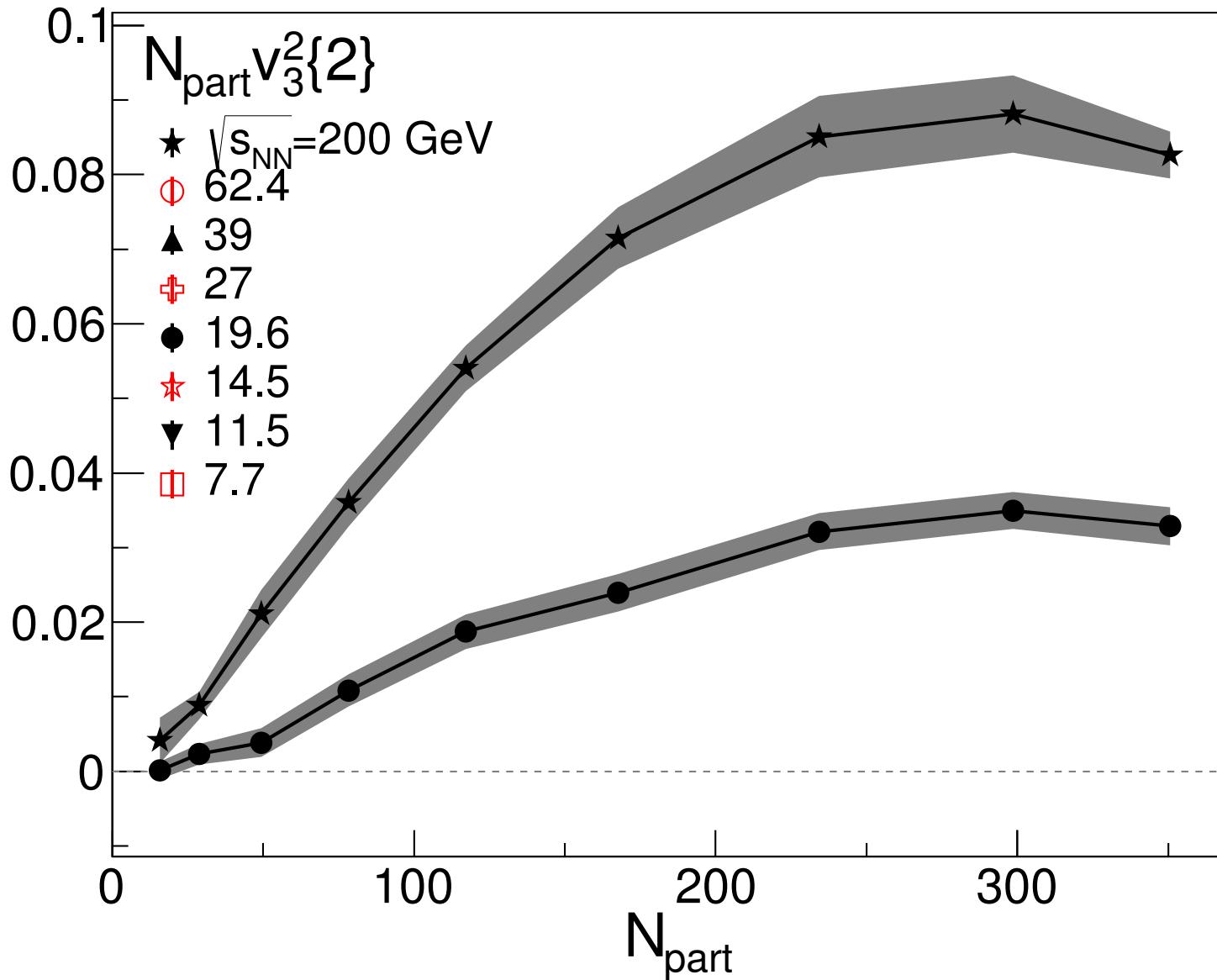
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



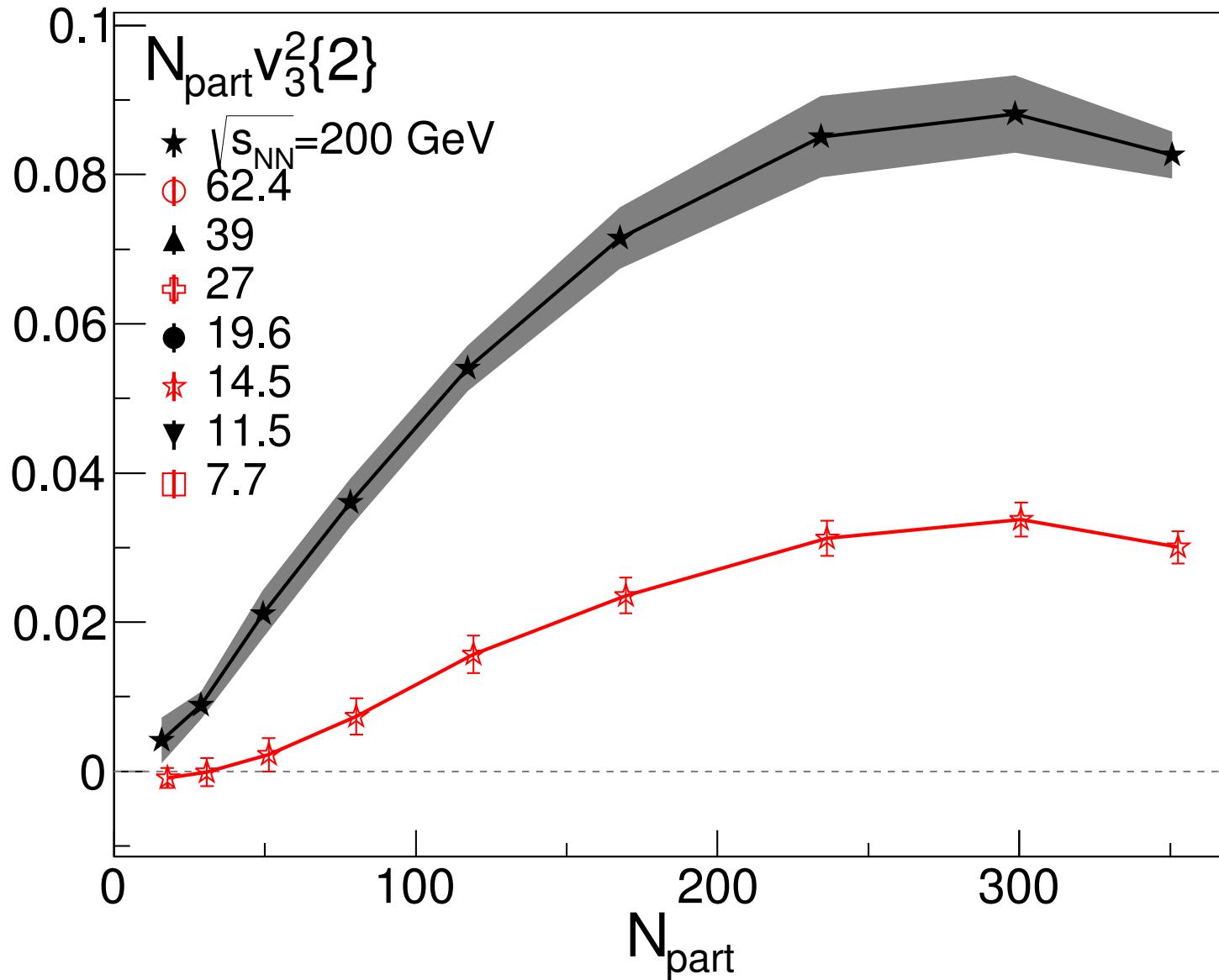
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



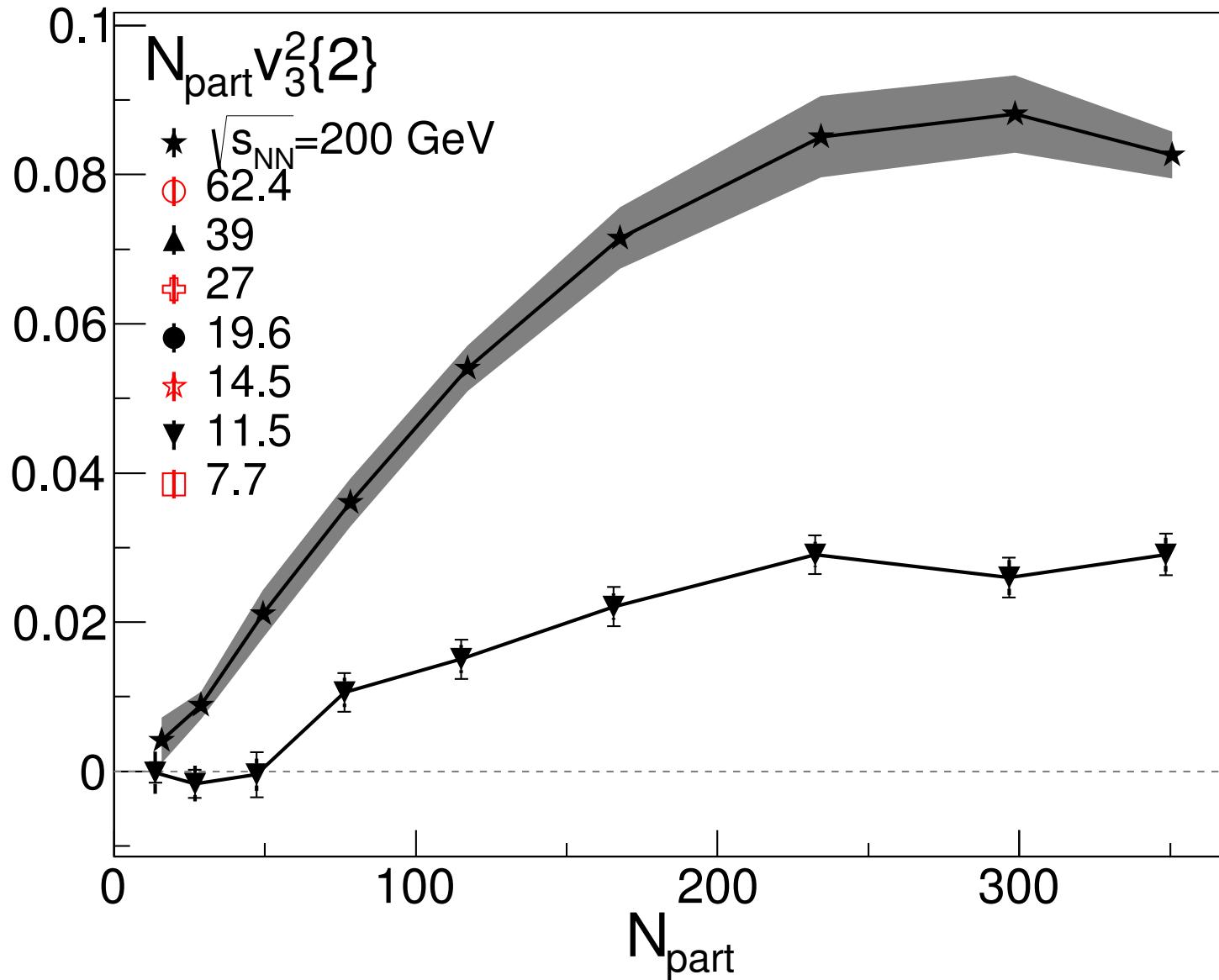
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



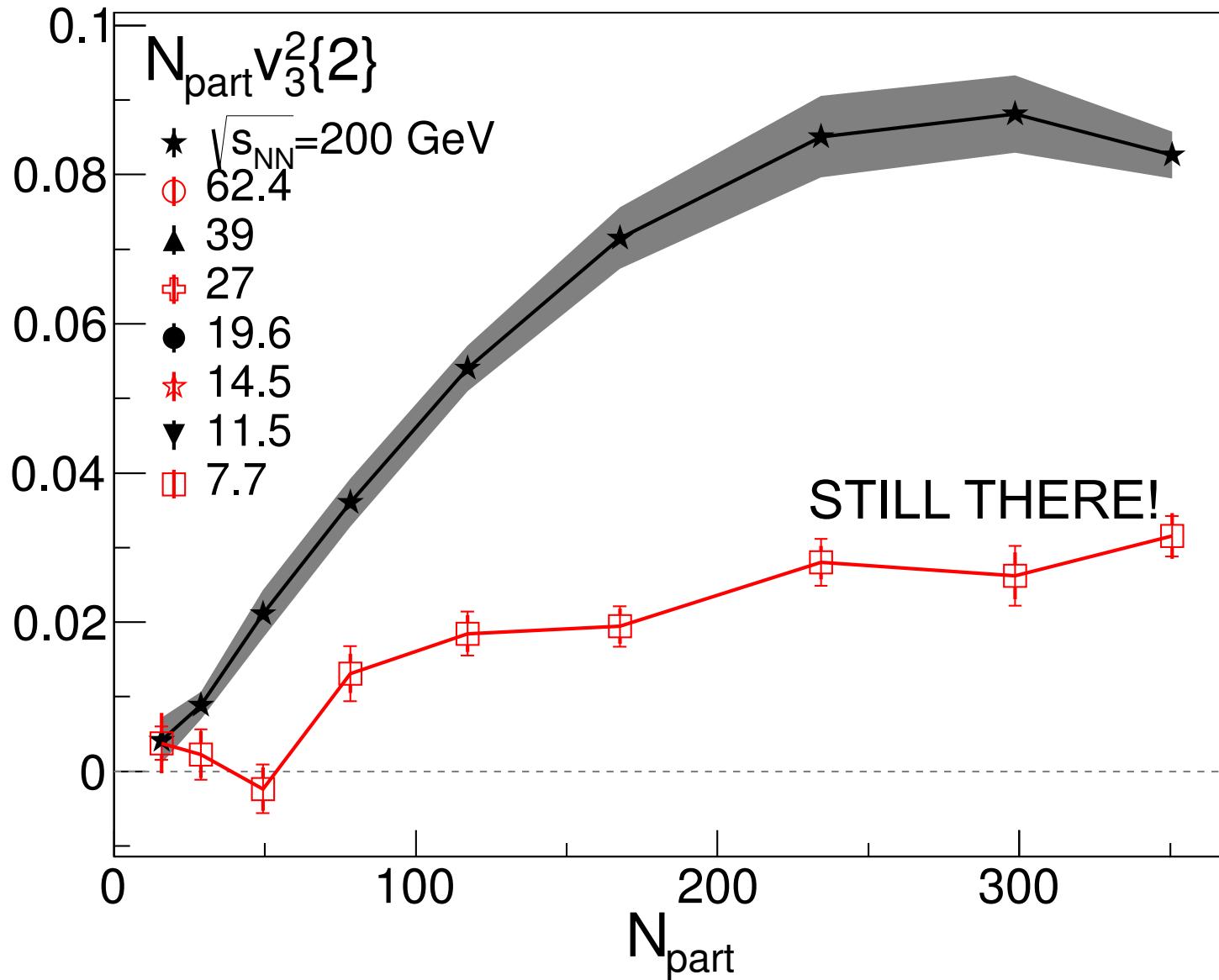
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



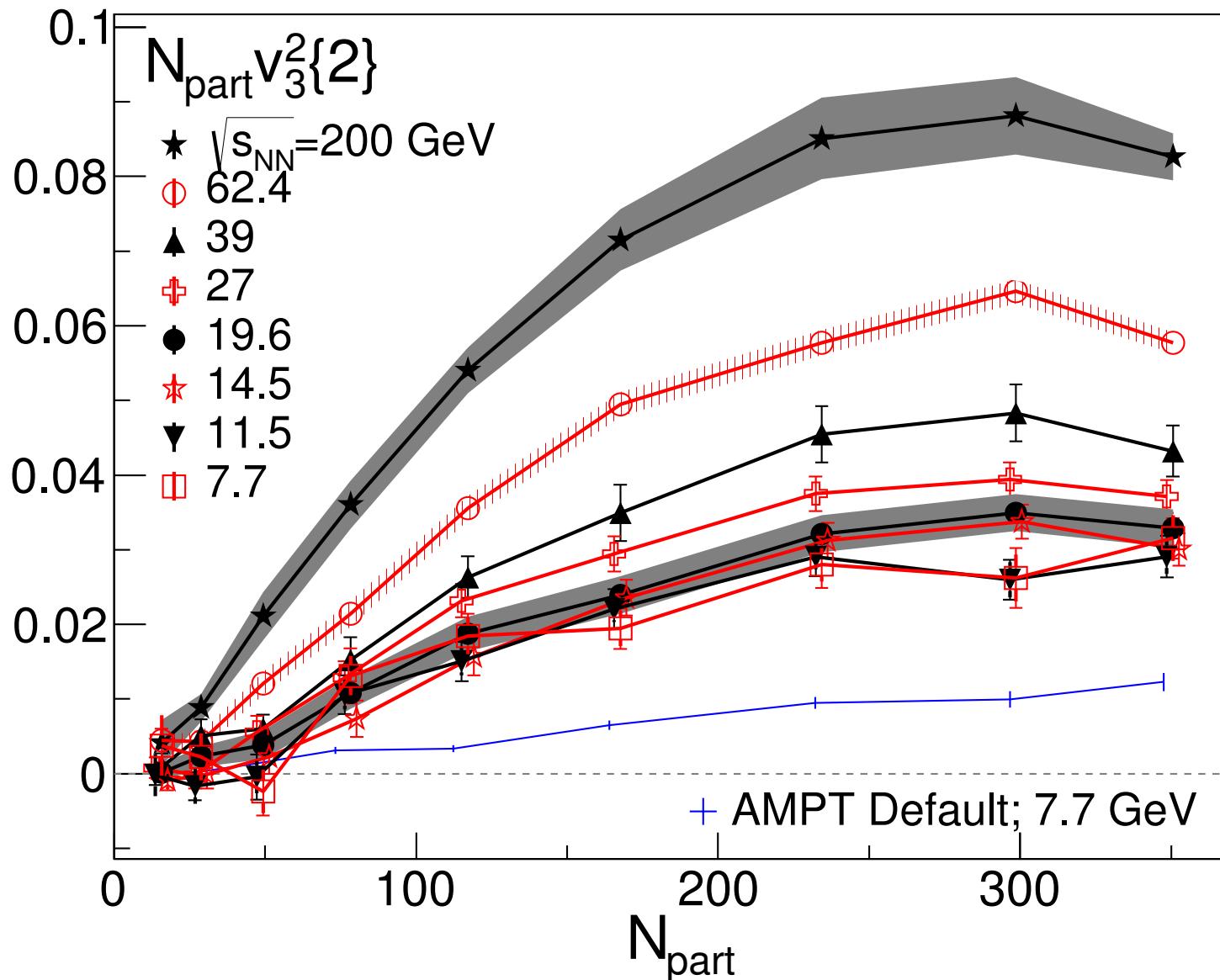
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



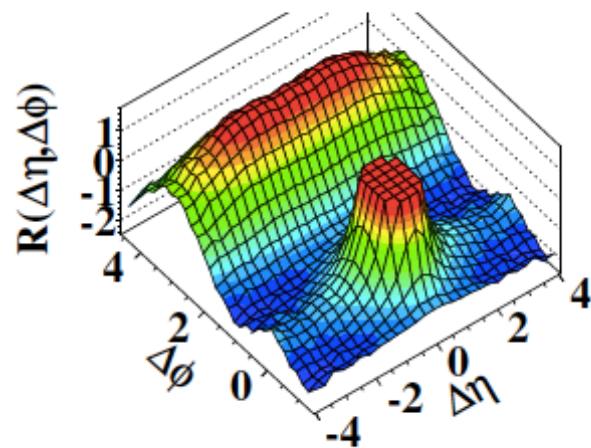
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302

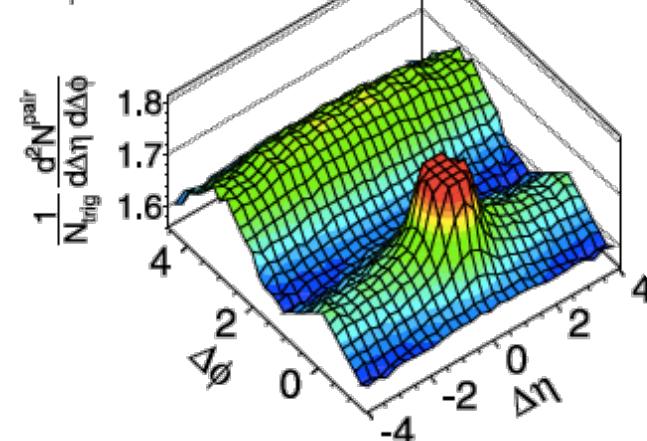


The Ridge and v_3 in Smaller Systems

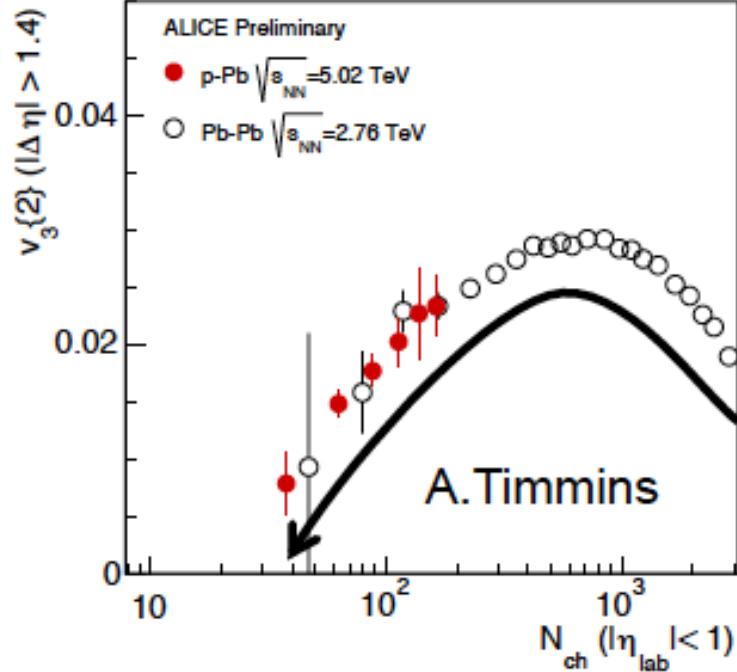
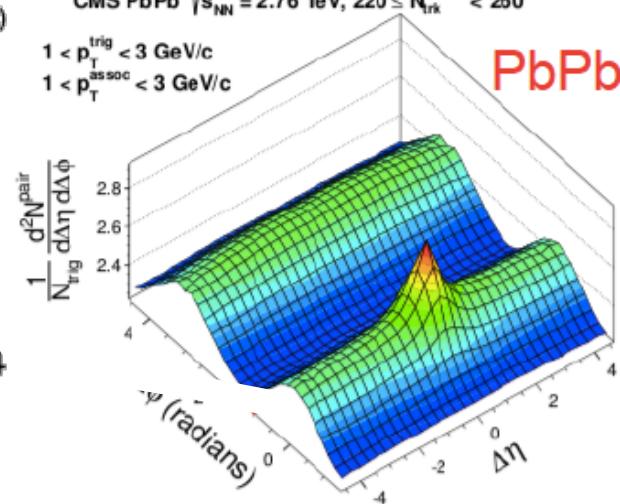
(d) CMS N ≥ 110 , $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



CMS pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $N_{\text{trk}}^{\text{offline}} \geq 110$
 $1 < p_T < 3 \text{ GeV}/c$



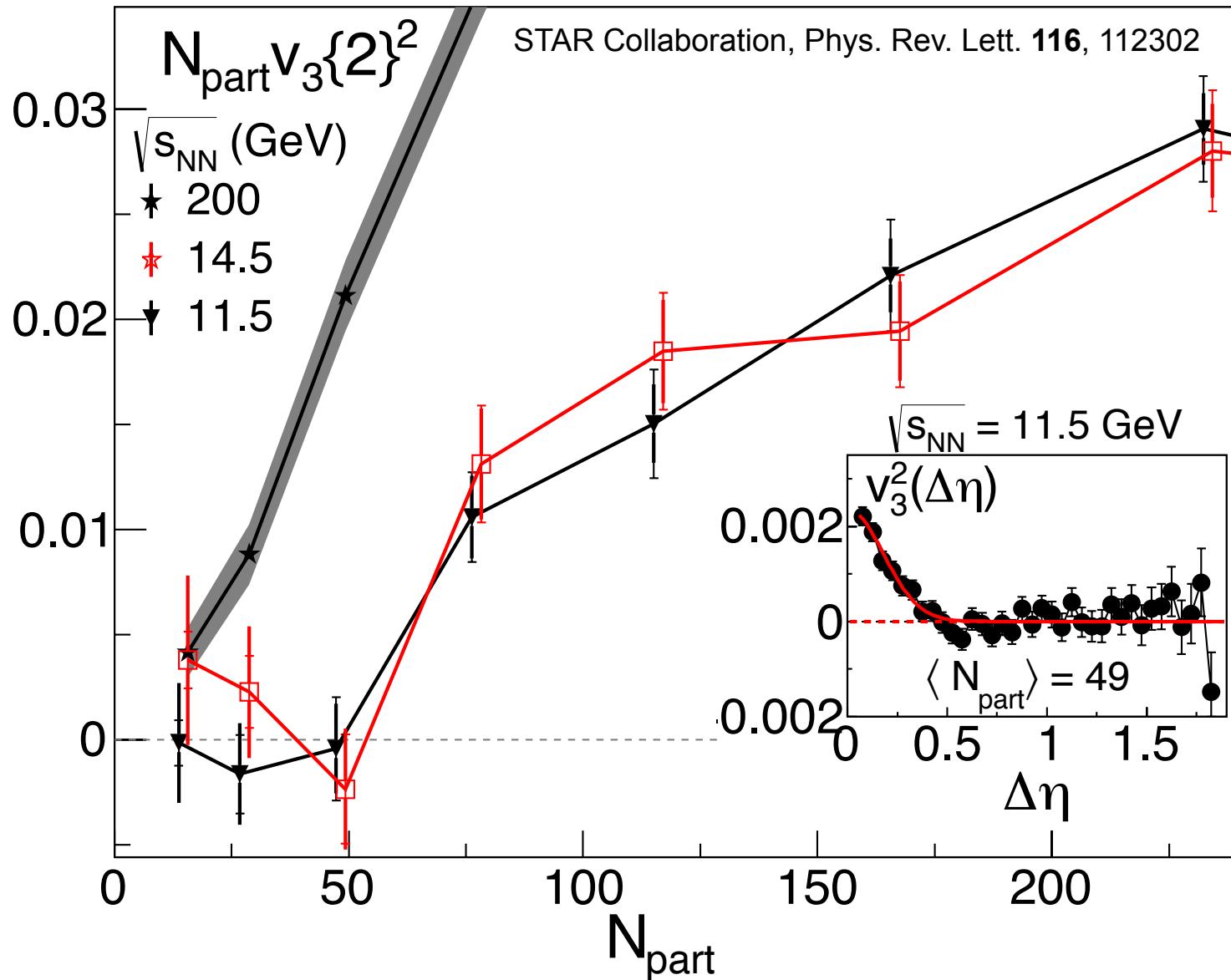
(b) CMS PbPb $\sqrt{s_{NN}} = 2.76 \text{ TeV}$, $220 \leq N_{\text{trk}}^{\text{offline}} < 260$
 $1 < p_T^{\text{trig}} < 3 \text{ GeV}/c$
 $1 < p_T^{\text{assoc}} < 3 \text{ GeV}/c$



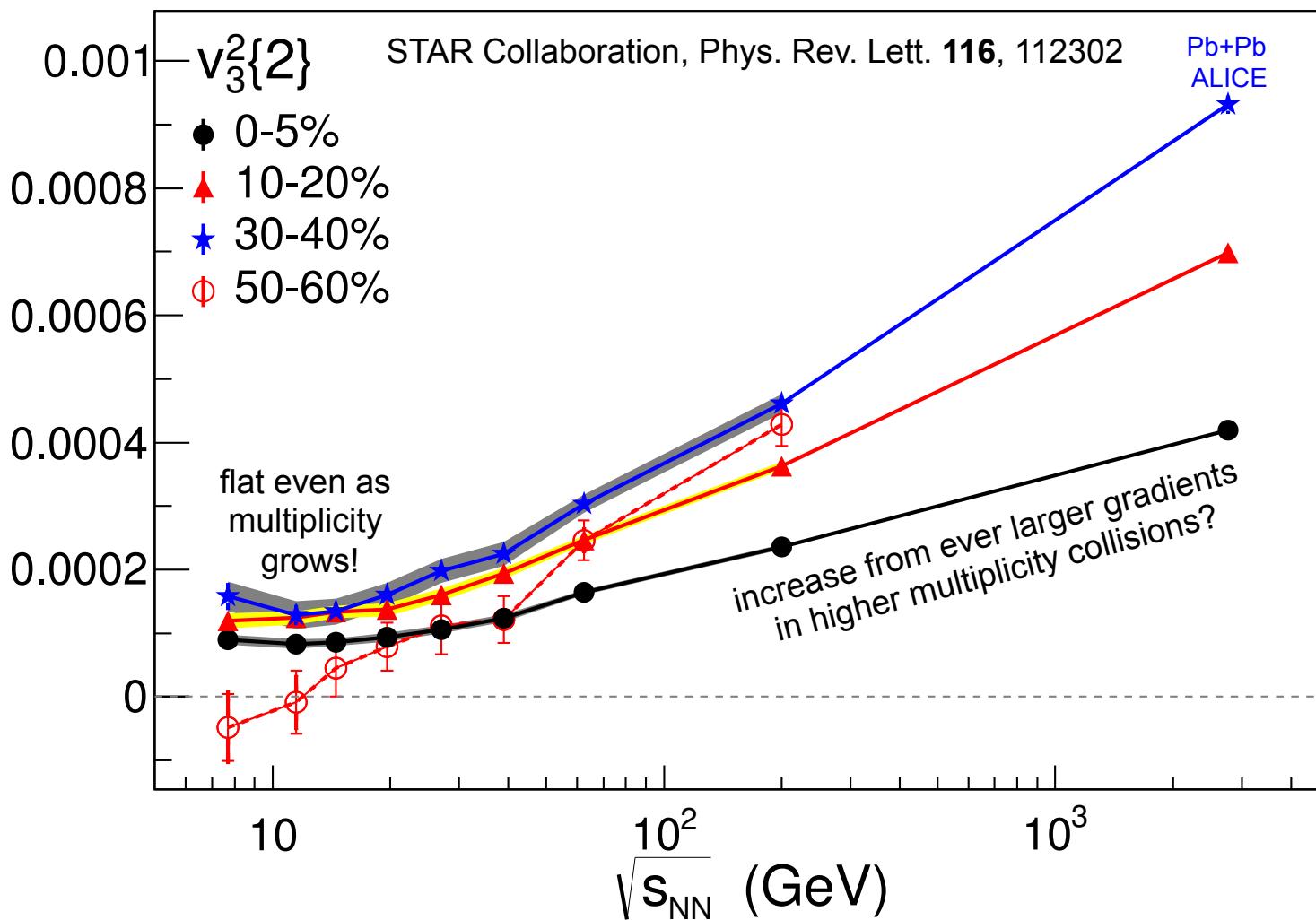
Ridge correlations in small systems;
considered by some to be a crisis...

Can we turn off the QGP?

Disappearance of v_3



Energy Dependence

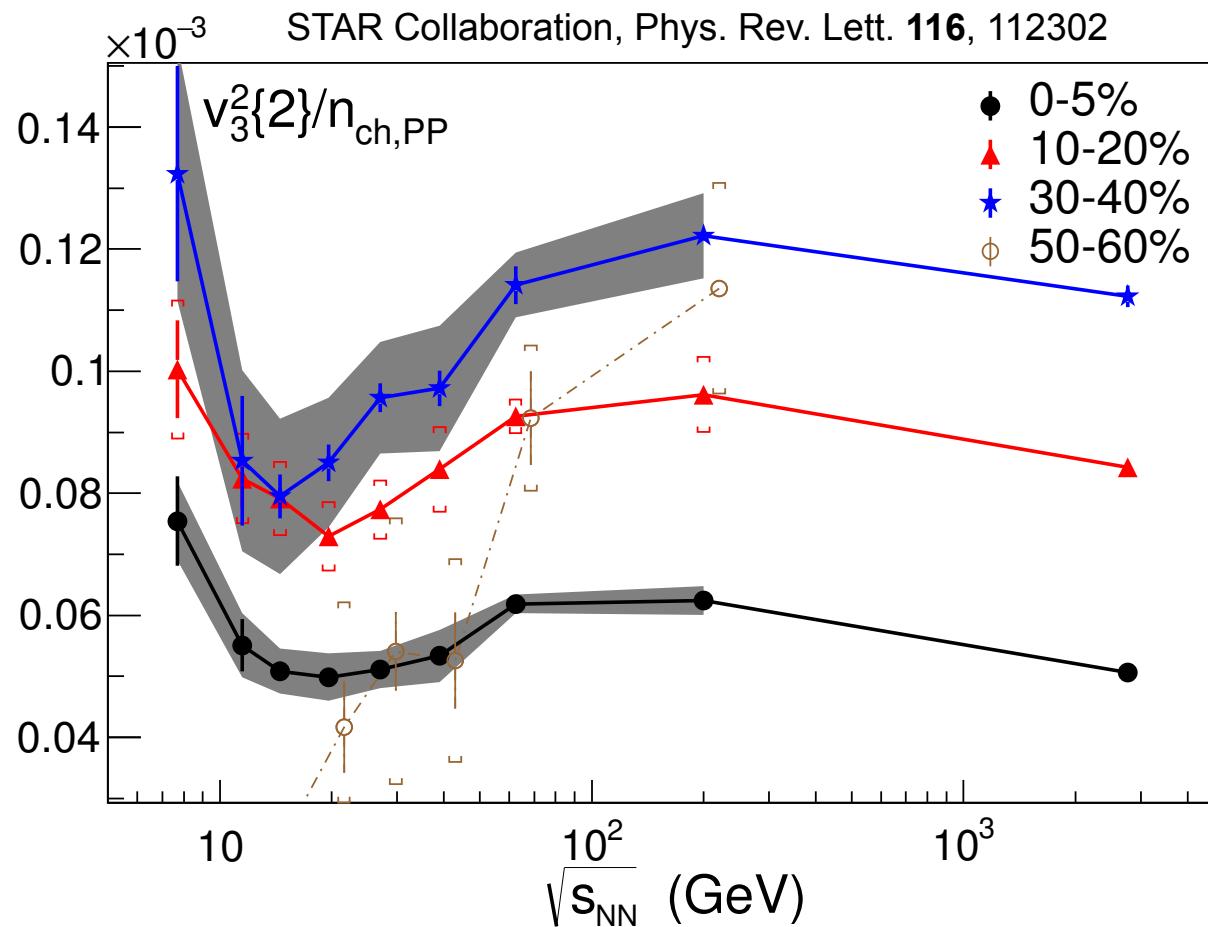


While the 3rd harmonic grows as $\sim \log(\sqrt{s})$ at higher energy, it is nearly independent of energy below 20 GeV.

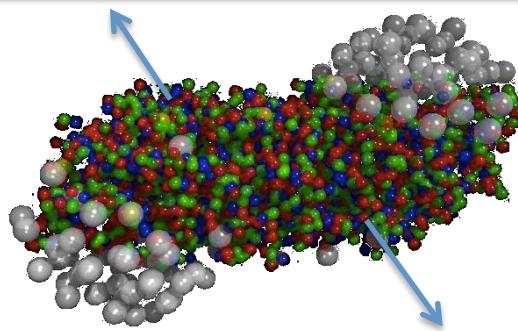
Anomalies in the Pressure?

Higher energy collisions producing more particles and higher pressure should more effectively convert fluctuations into v_3 .

Deviations from that expectation could be indicative of interesting trends like a slowing of the speed of sound. [What does \$v_3^2/N_{ch}\$ look like?](#)

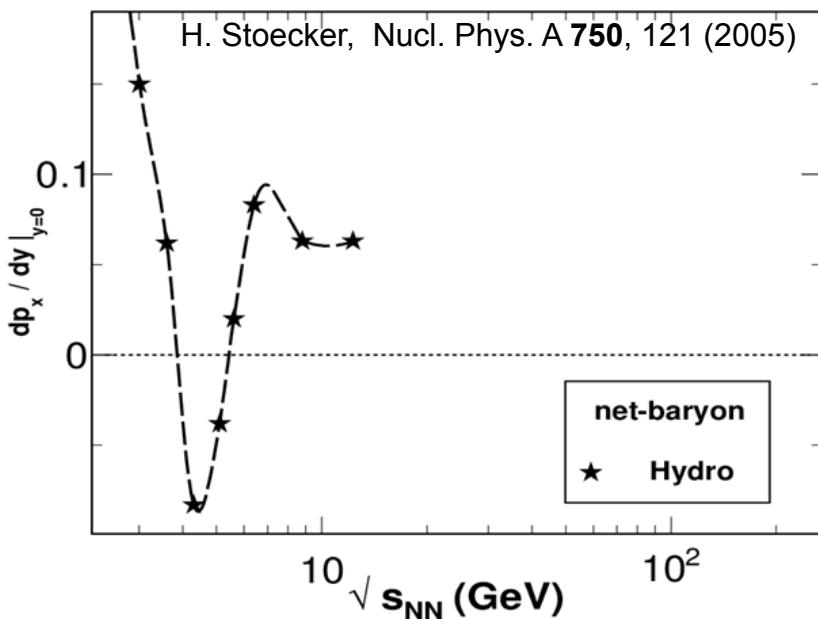


Anomalies in the Pressure?

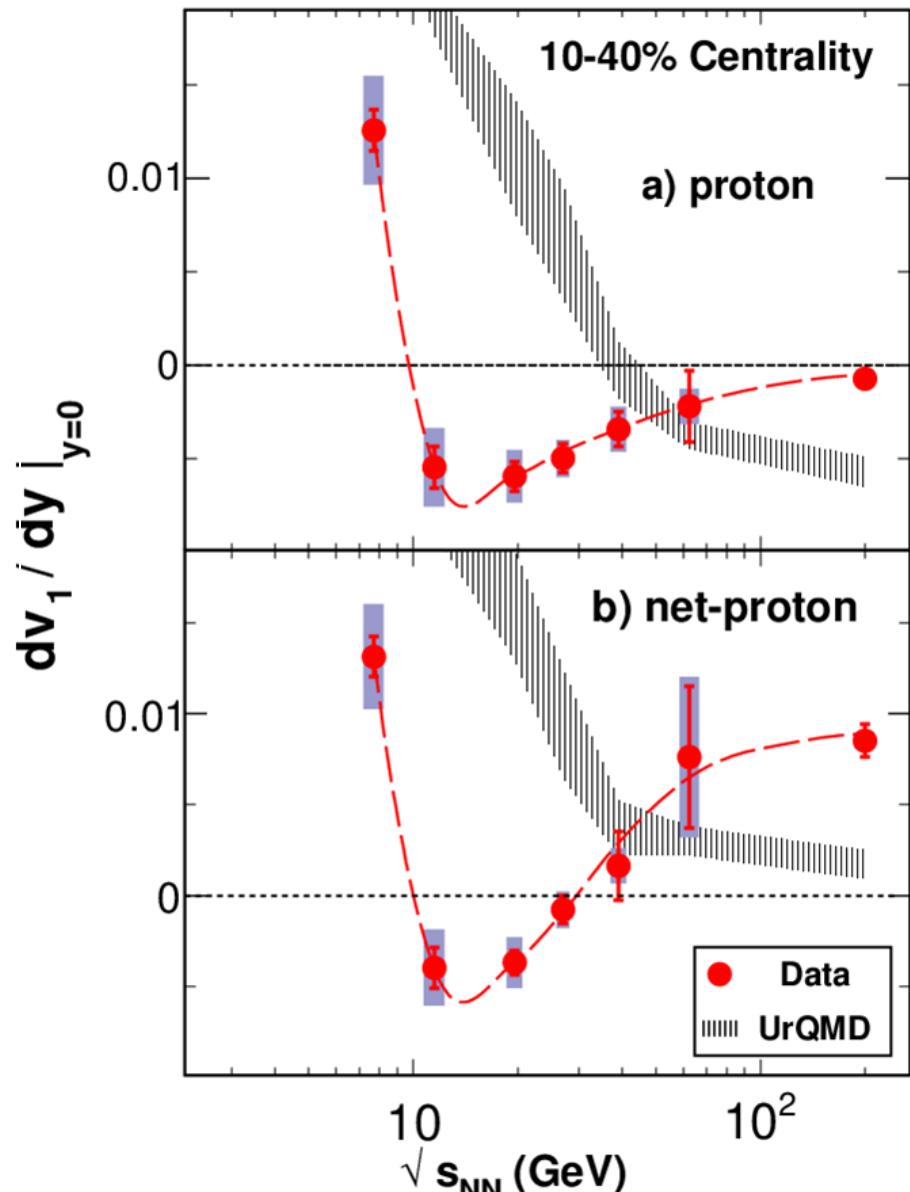


v_1 for both p & net- p qualitatively resemble collapse signature

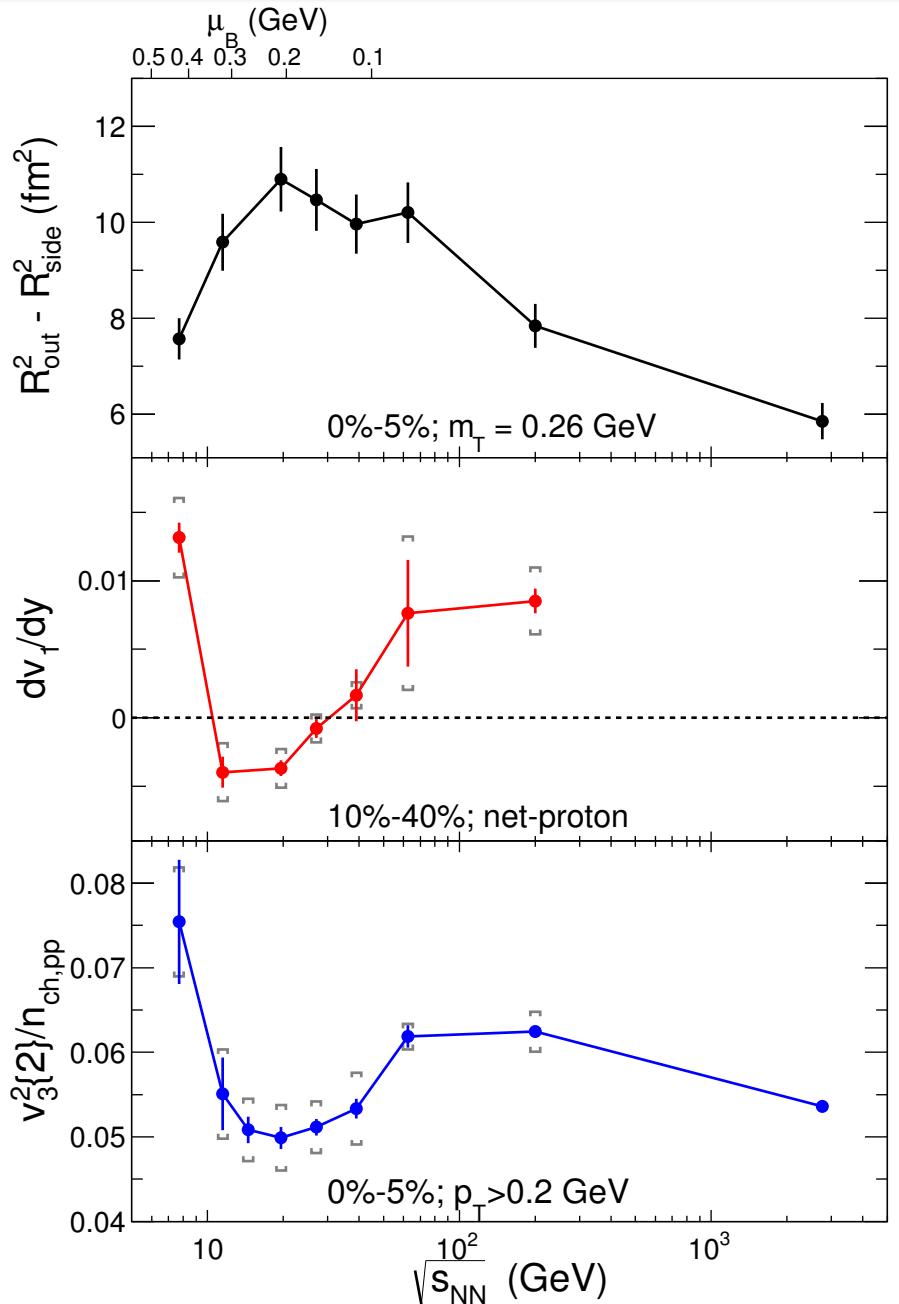
Calculations with more sophisticated treatments of early times are needed



STAR, PRL **112**, 162301 (2014); arXiv:1401.3043



Are Data Indicative of Anomalies in the Pressure?

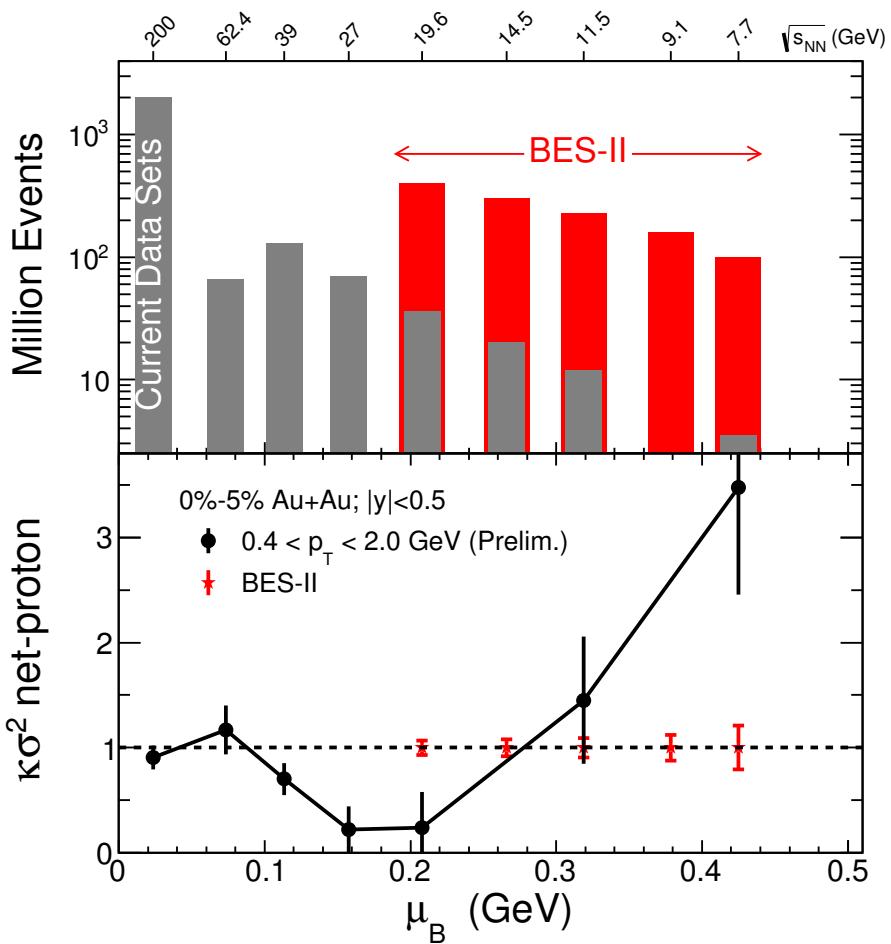


Maximum in lifetime?
Minimum in pressure?
Region of interest $\sqrt{s_{NN}} \sim 20$ GeV, however, is complicated by a changing B/M ratio, baryon transport dynamics, longer nuclear crossing times, etc.
Requires concerted modeling effort: the work of the BEST collaboration is essential

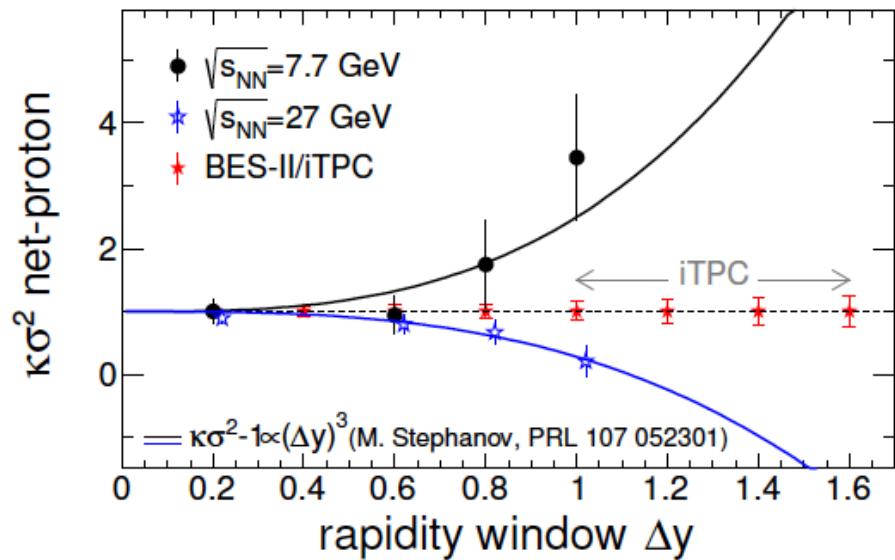
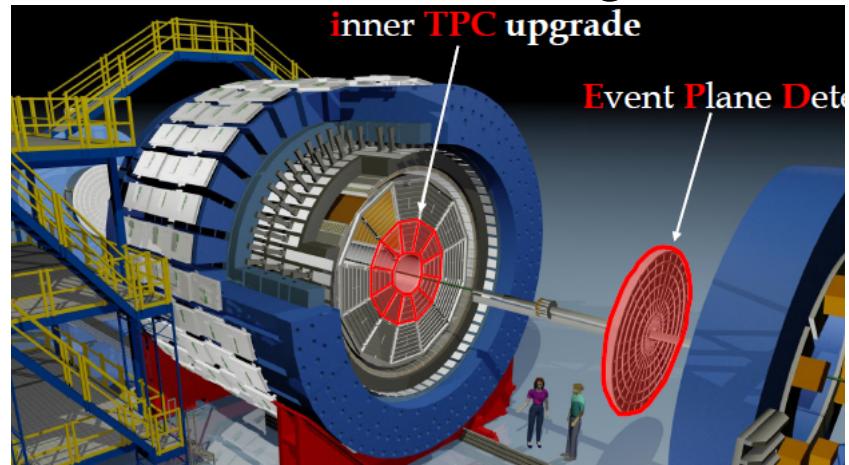
Mapping the region of interest: BES-II

More Data

RHIC Luminosity Upgrade for Low Energies



Better Coverage



BES-II: detector and accelerator upgrades for 2019 and 2020

What I hope you took away from today

Models suggest v_3 is a good indicator for the presence of a low viscosity QGP phase

Measurements show that for sufficiently central collisions, v_3 persists down to the lowest energies at RHIC

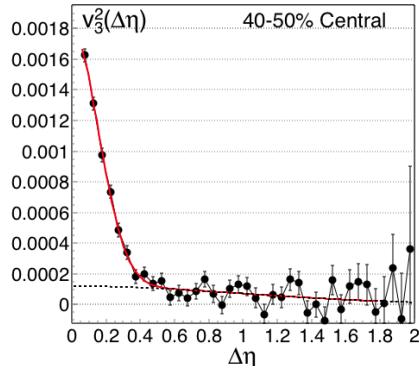
For peripheral collisions however, we find that v_3 disappears in lower energy collisions: Turn off of the QGP

The energy dependence of v_3 and other observables seems to suggest an anomalously low pressure in the matter created in heavy ion collisions with \sqrt{s}_{NN} near 15-20 GeV

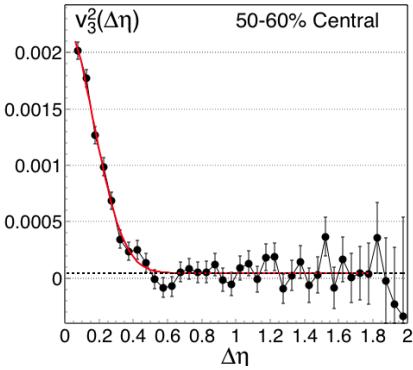
Thanks

Disappearance of v_3

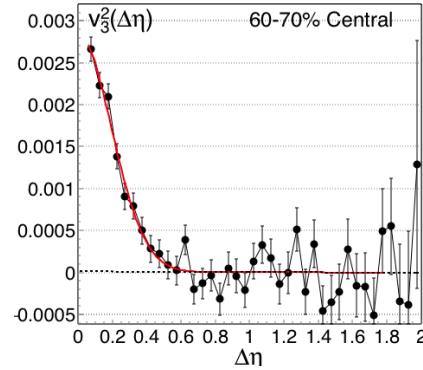
40-50%



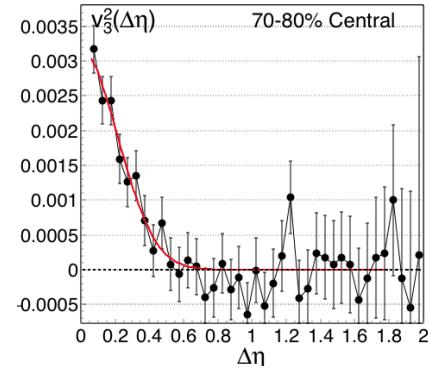
50-60%



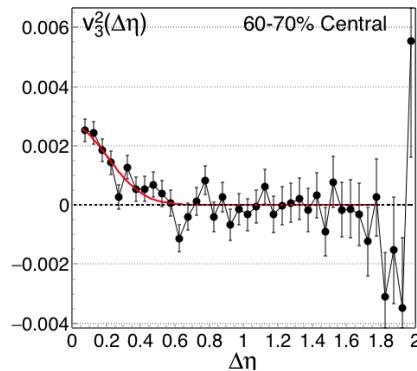
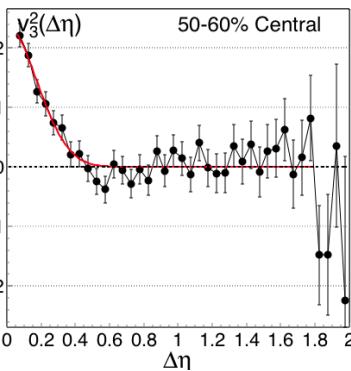
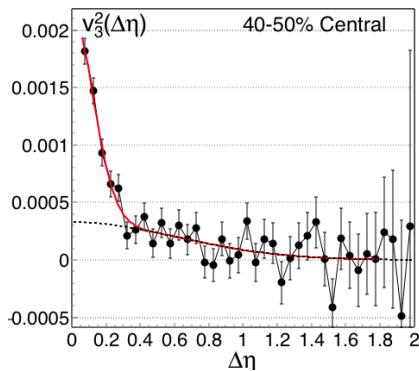
60-70%



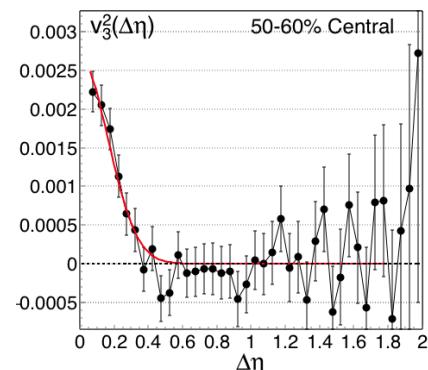
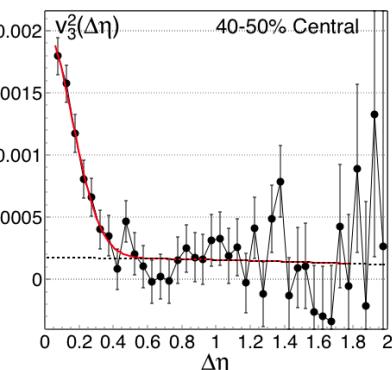
70-80%



14.5 GeV

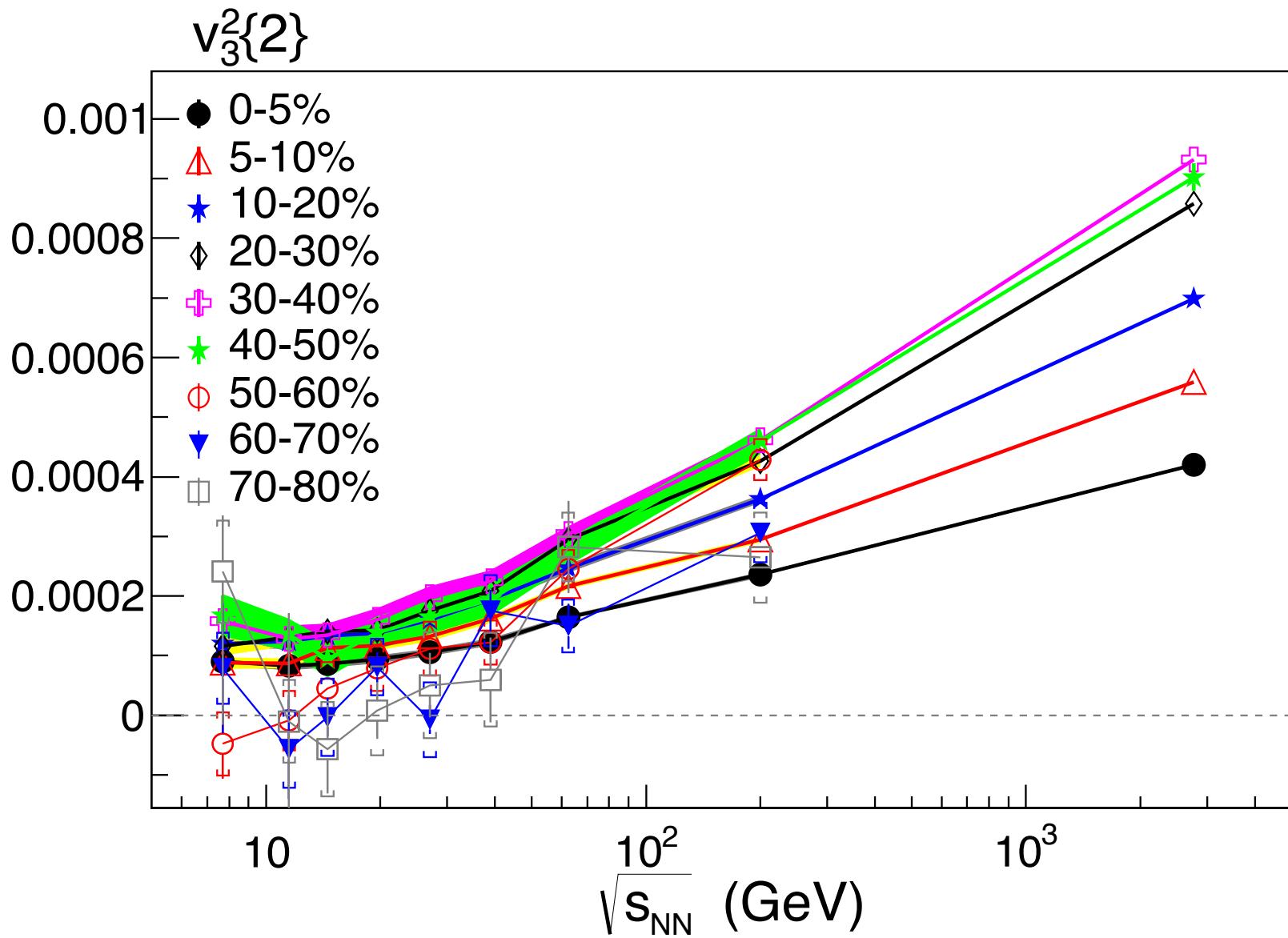


11.5 GeV



7.7 GeV

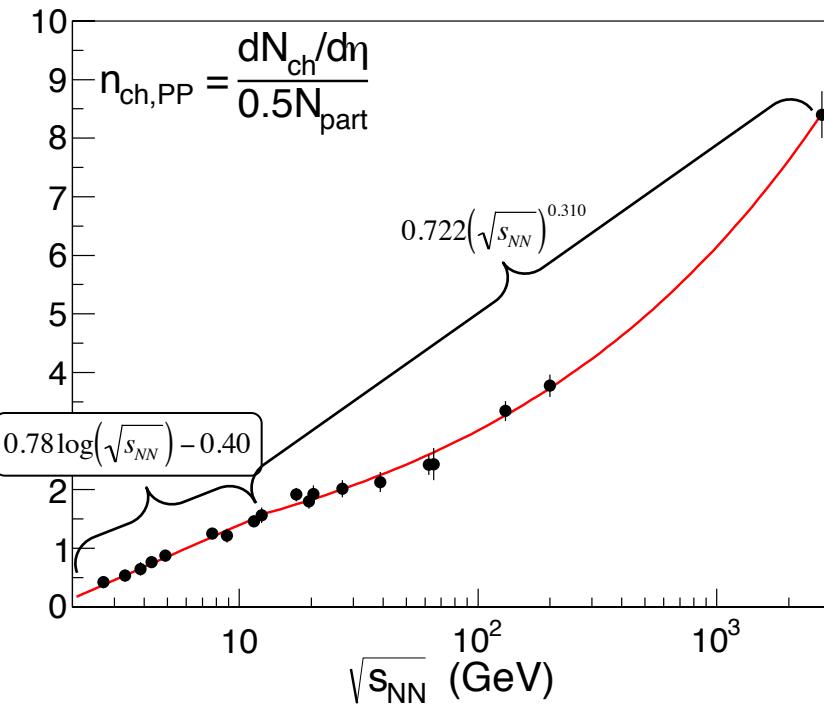
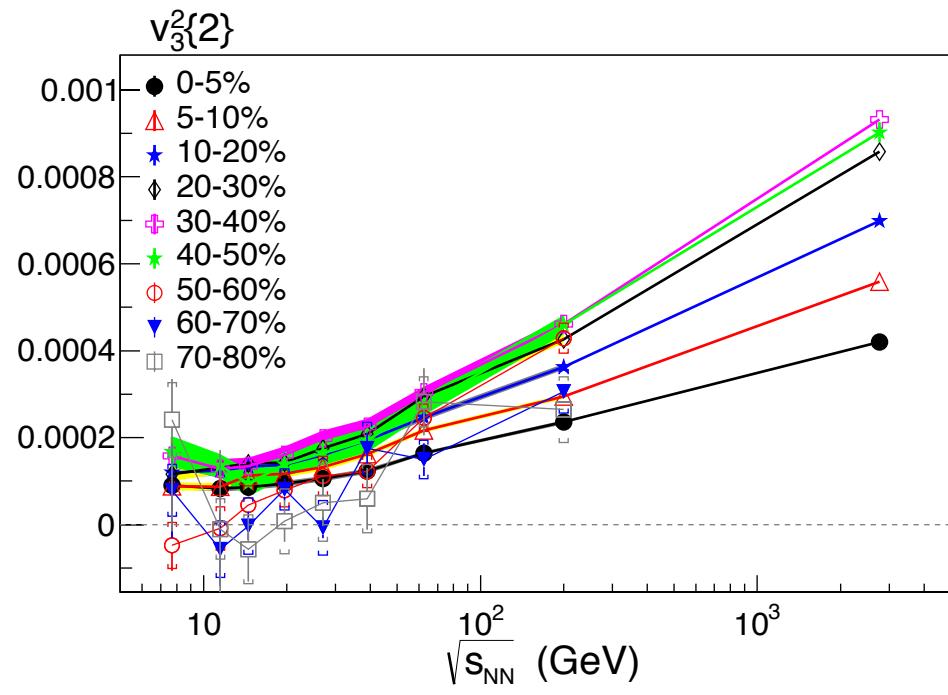
All Centralities



Increasing Multiplicity

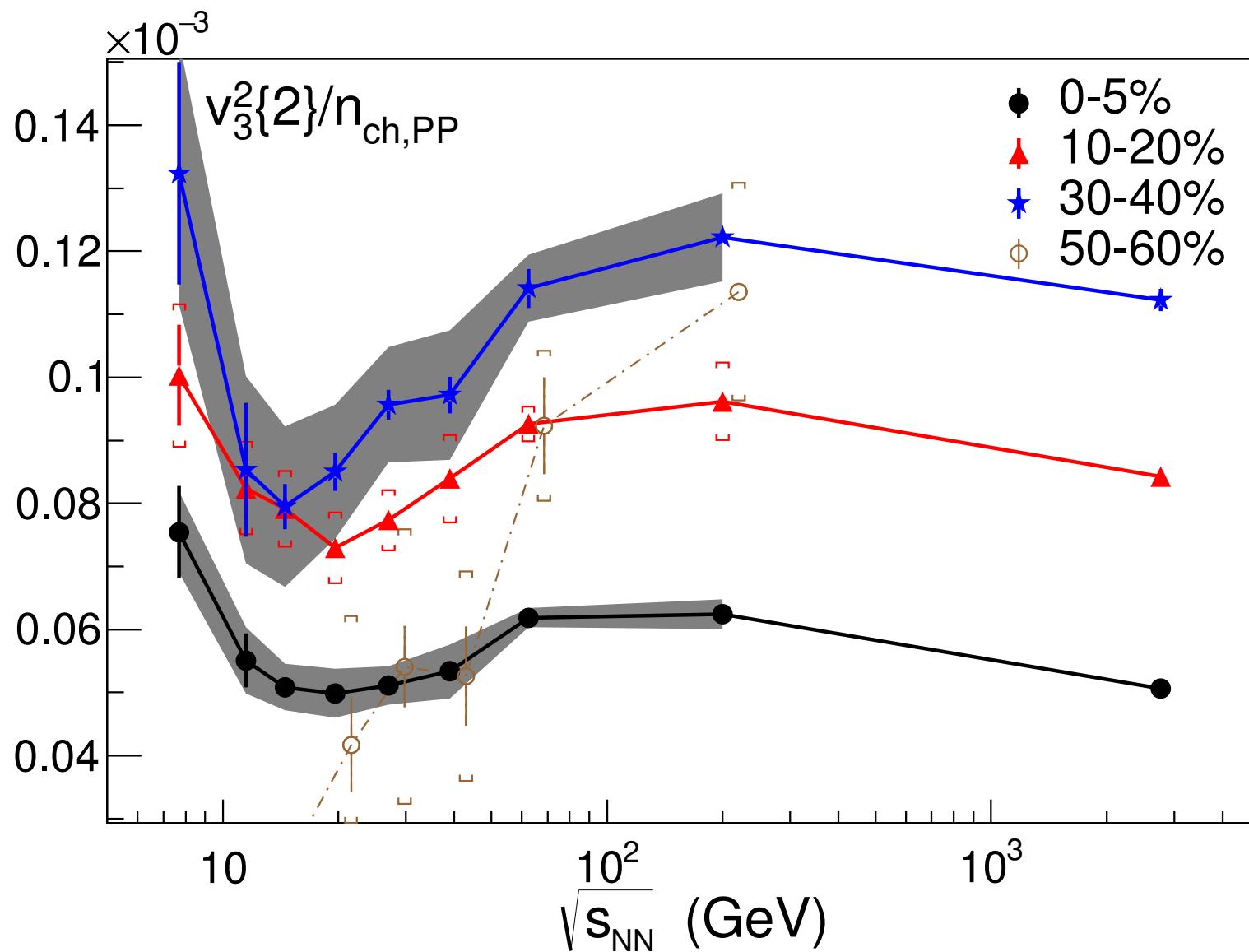
Independent of energy range, one expects higher energy collisions producing more particles to more effectively convert geometry fluctuations into v_3 .

Deviations from that expectation could be indicative of interesting trends like a softening of the equation of state. What does v_3^2/N_{ch} look like?

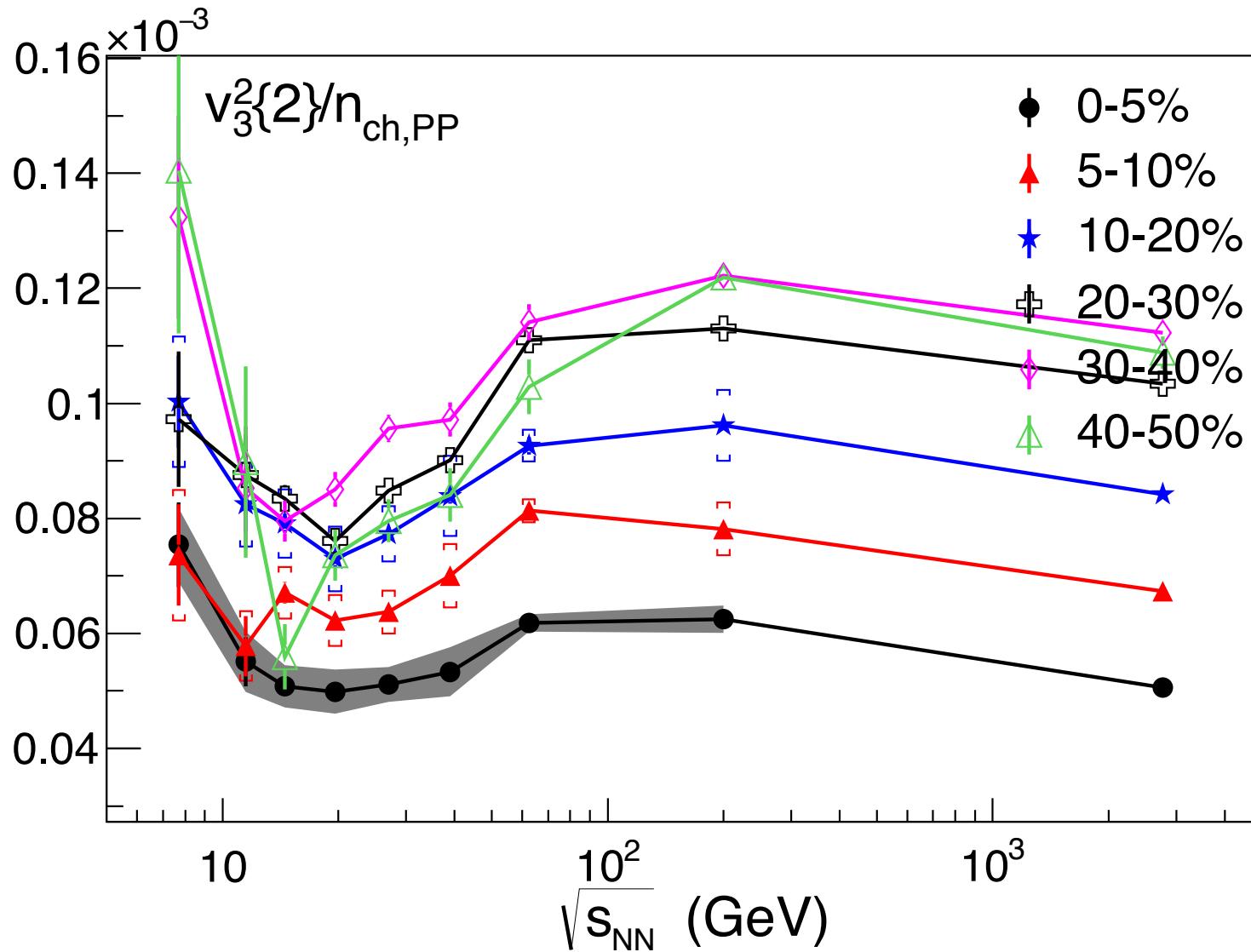


We parameterize the world's data and take the ratio

Softening?

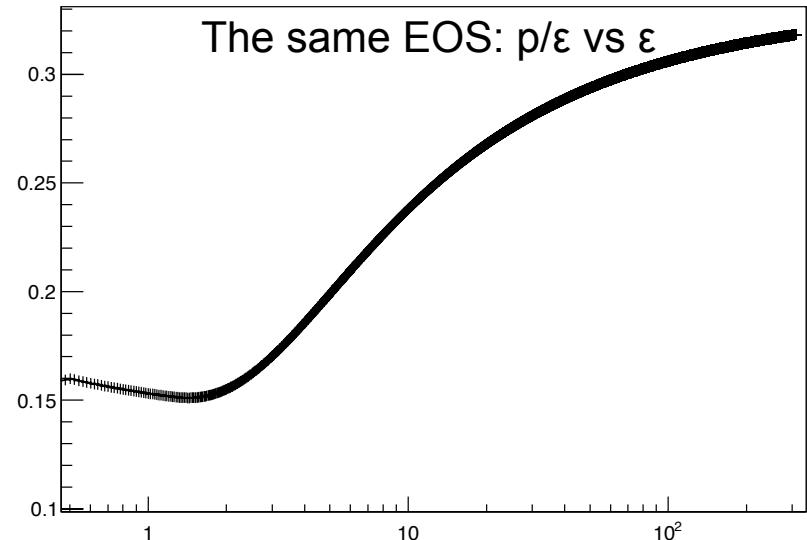
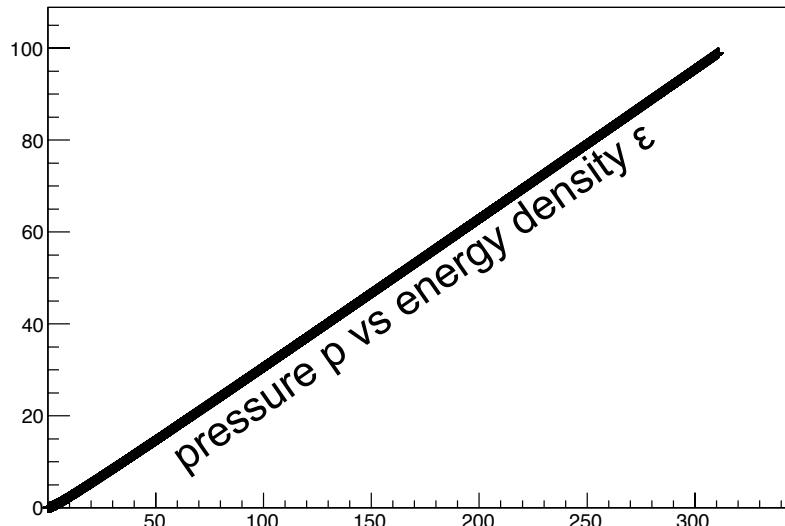


Softening?



Local minima is present for all centralities between 0 and 50%

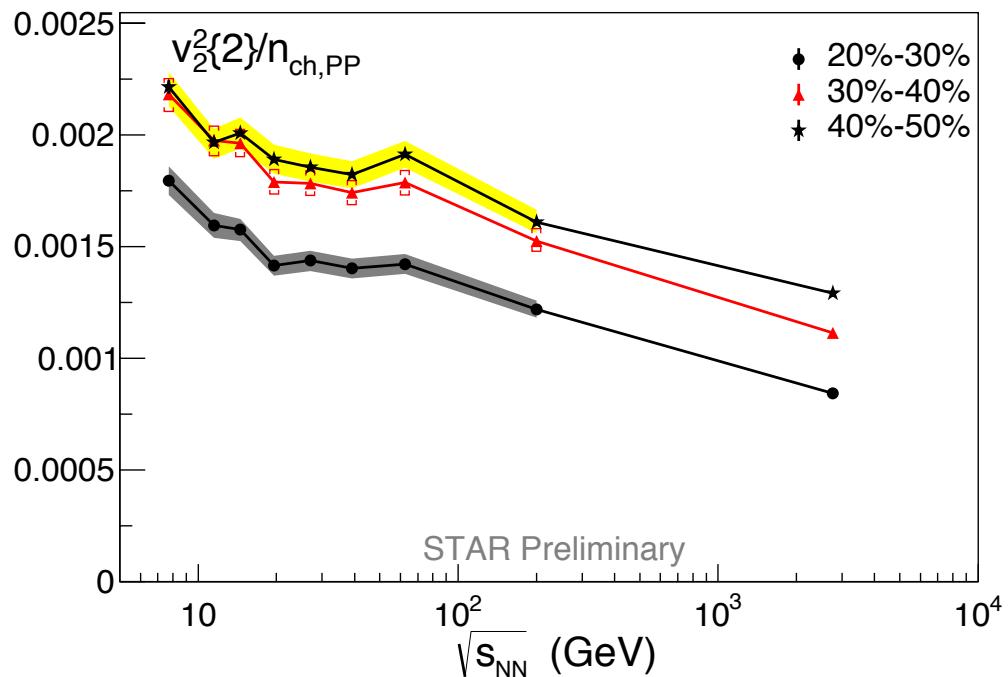
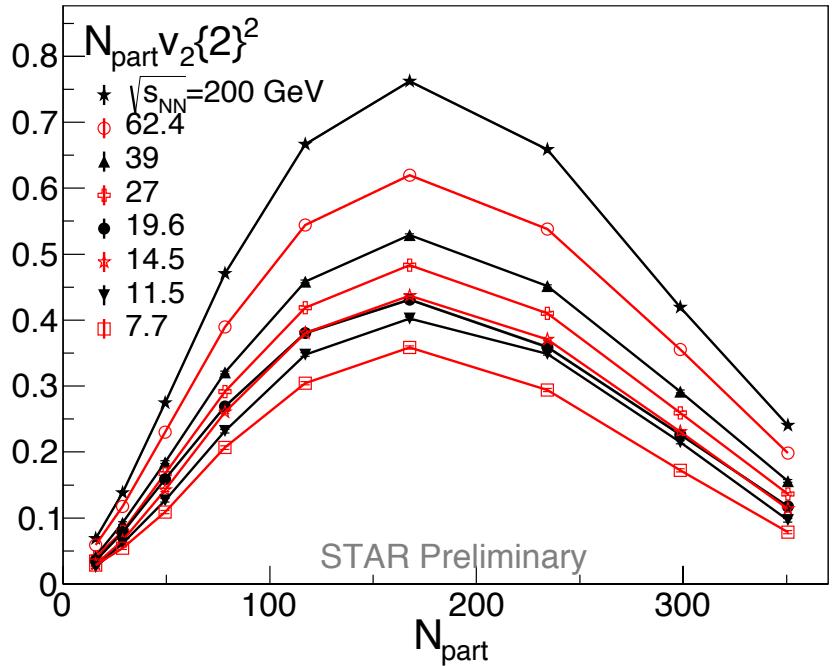
Lattice EOS



Plotting format matters!

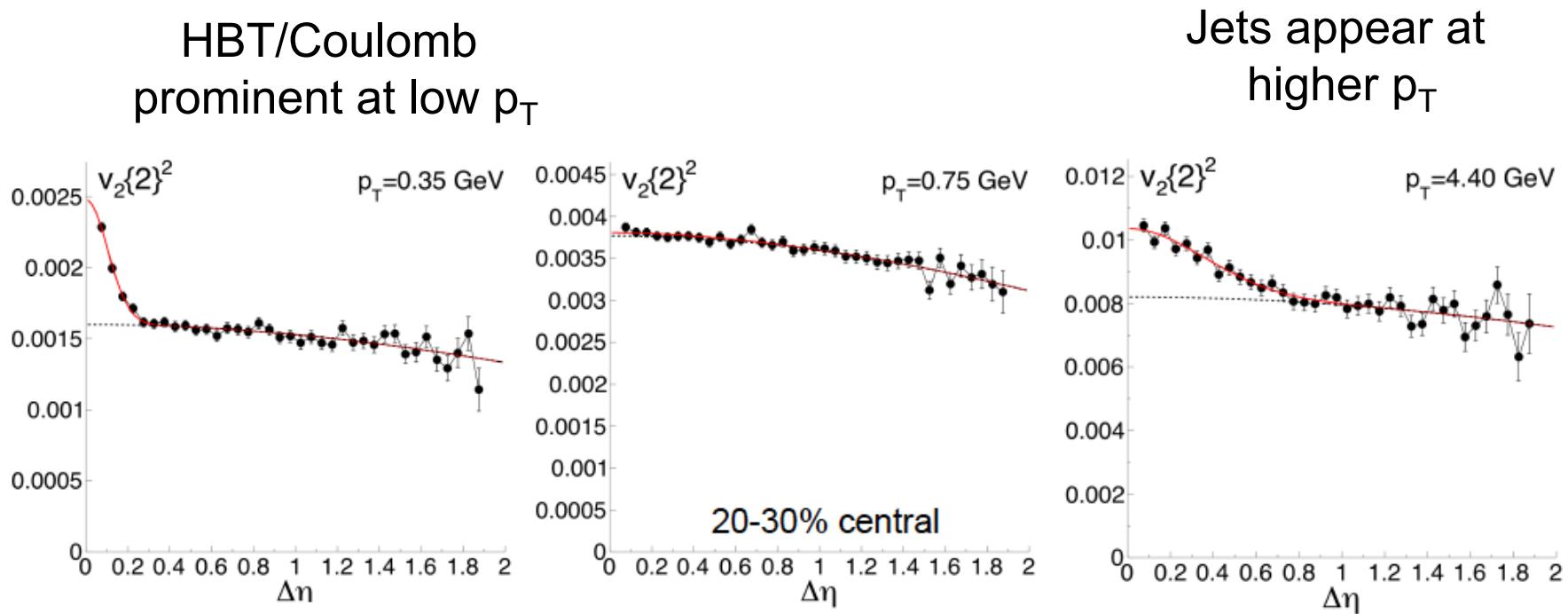
especially when looking for trends in pressure vs energy density

What about v_2 ?

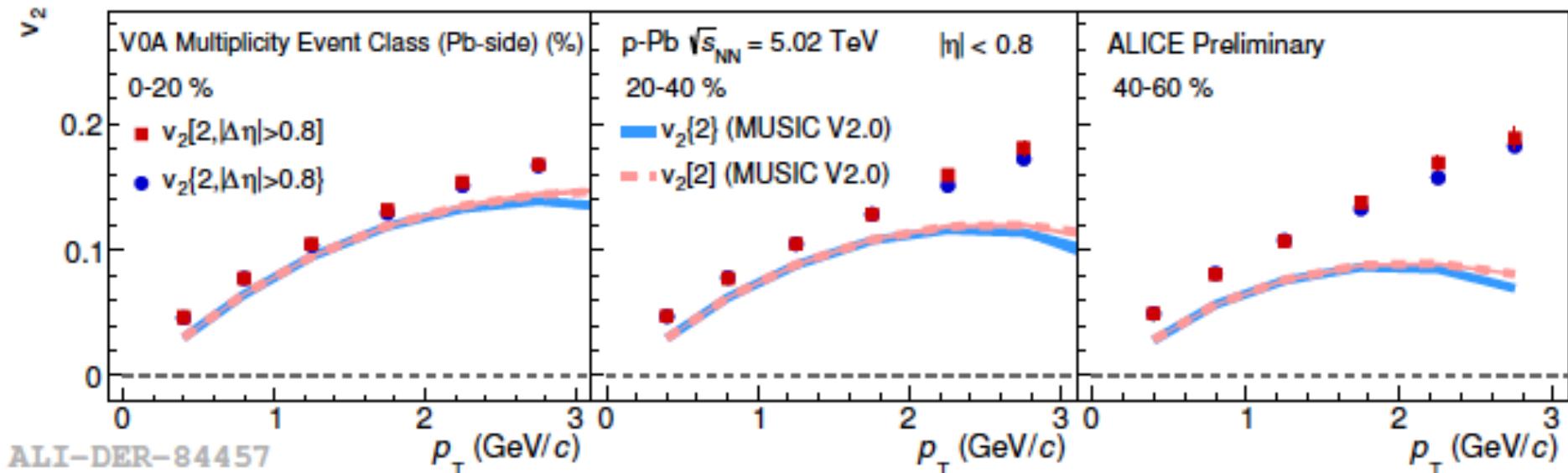


p_T Dependence of the Decomposition

Short range correlations can be subtracted by looking at the $\Delta\eta$ dependence

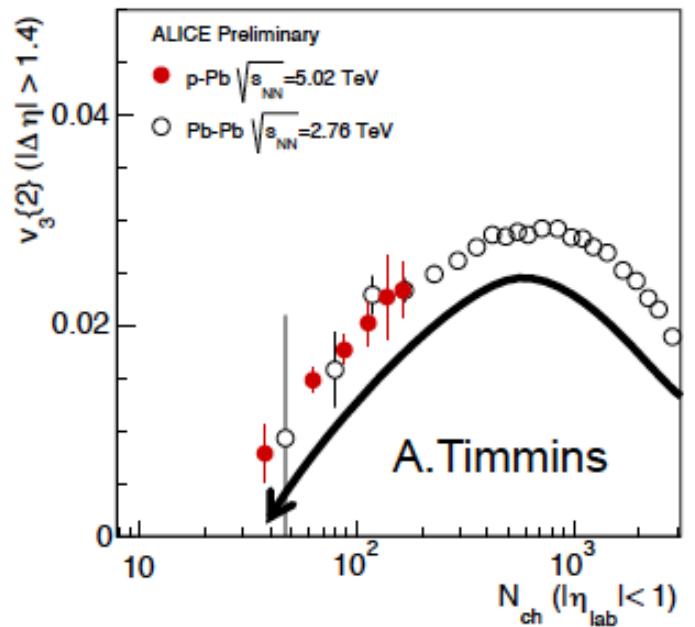


Correlations in Small Systems



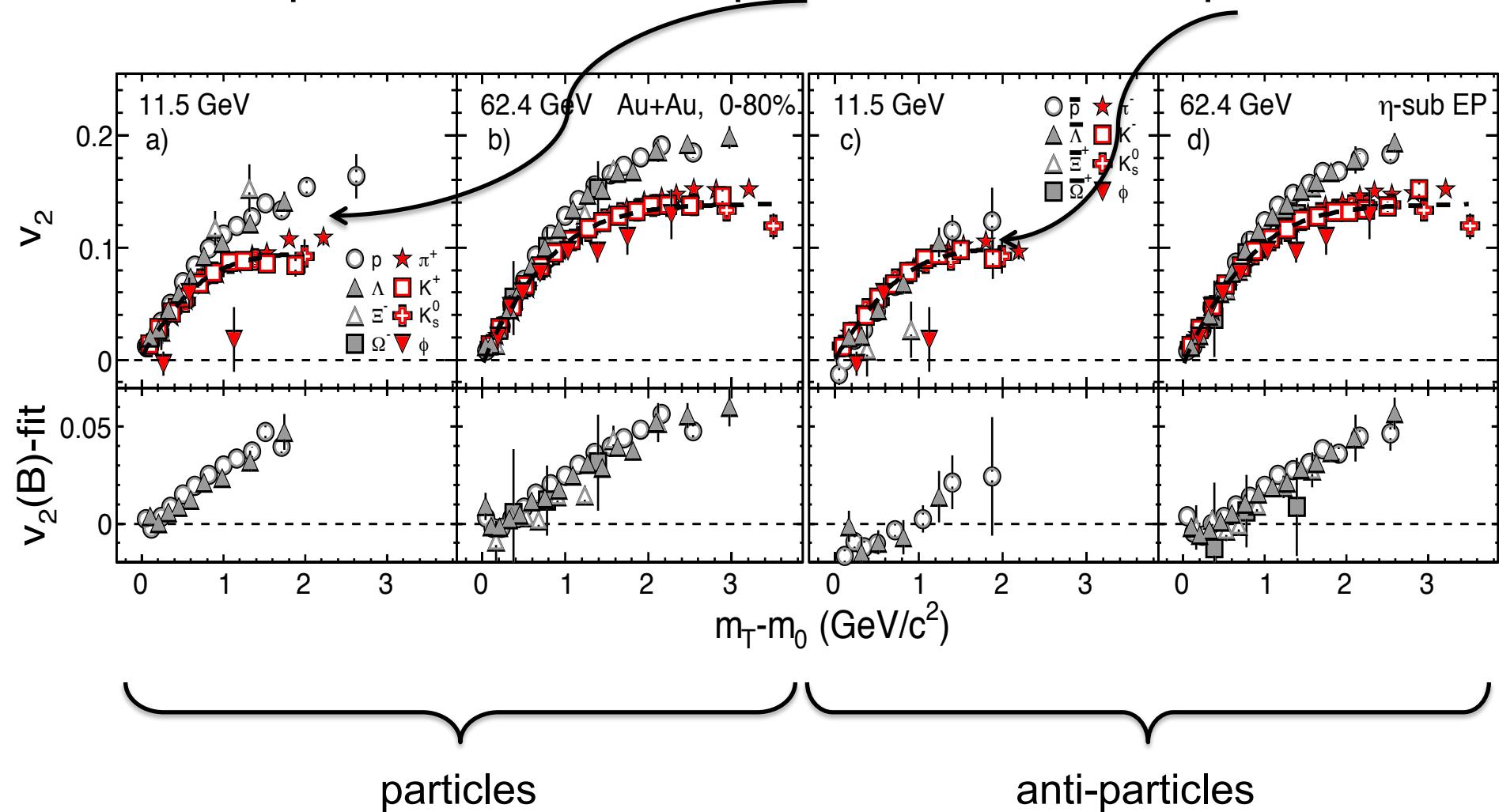
Hydro-based dynamic calculations also start to agree with the data for central p+Pb collisions

Surprisingly smooth continuity across multiplicities from 30 to 3000 (but what should we have expected?)

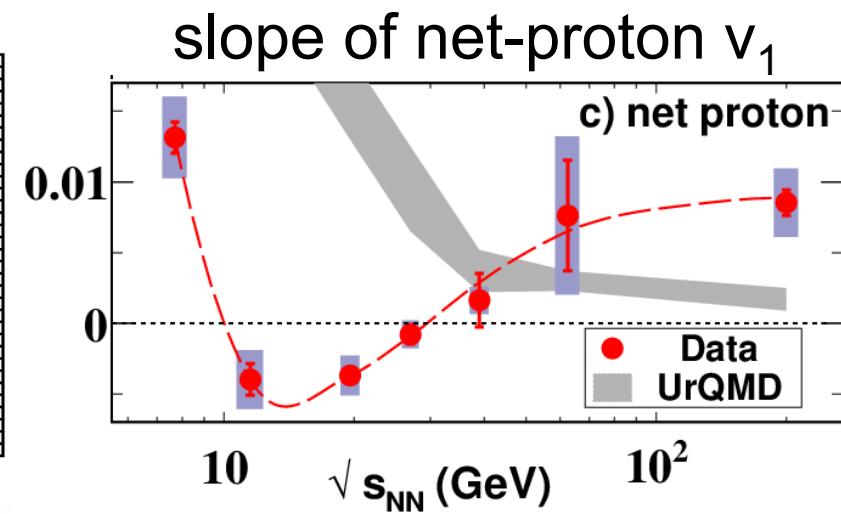
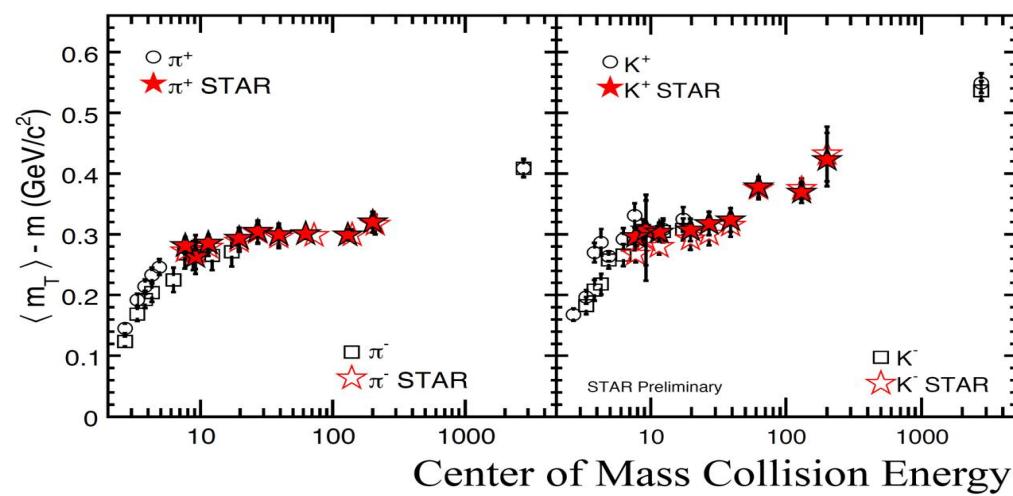
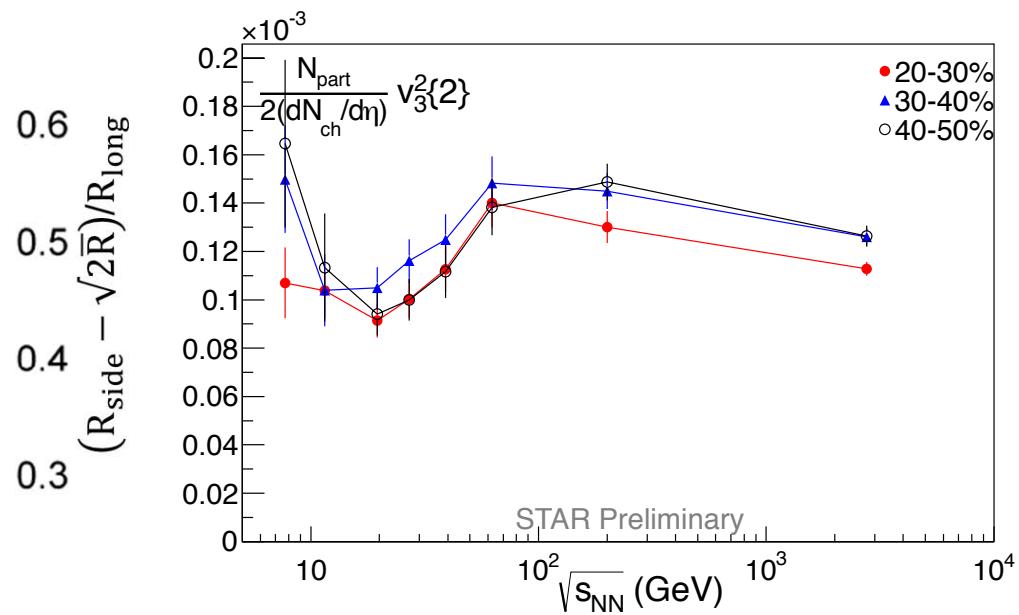
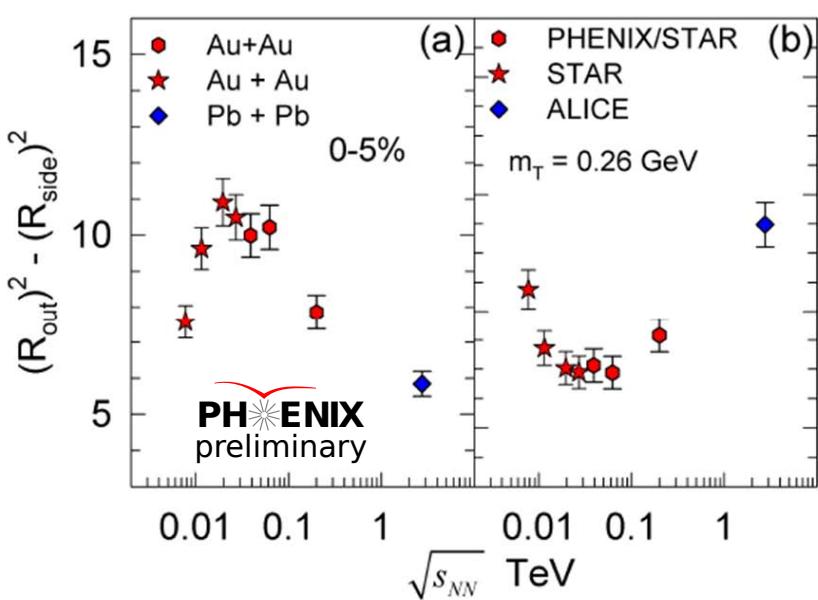


v_2 from 2.76 TeV down to 7.7 GeV

At low energy,
NCQ dependence holds for particles but not anti-particles



Non-monotonic trends in pressure?



Statistics Needed in BES phase II

Collision Energies (GeV):	7.7	9.1	11.5	14.5	19.6
Chemical Potential (MeV):	420	370	315	260	205
Observables	Millions of Events Needed				
R_{CP} up to p_T 4.5 GeV	NA	NA	160	92	22
Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400
Local Parity Violation (CME)	50	50	50	50	50
Directed Flow studies (v_1)	50	75	100	100	200
asHBT (proton-proton)	35	40	50	65	80
net-proton kurtosis ($\kappa\sigma^2$)	80	100	120	200	400
Dileptons	100	160	230	300	400
Proposed Number of Events:	100	160	230	300	400